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**Casey et al.**

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(54) **INTEGRATED CIRCUIT INCLUDING A CONTINUOUS TIME LINEAR EQUALIZER (CTLE) CIRCUIT AND METHOD OF OPERATION**

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**H04L 25/02** (2006.01)  
**H04L 27/01** (2006.01)

(52) **U.S. Cl.**  
CPC .... **H04L 25/03885** (2013.01); **H04L 25/0212** (2013.01); **H04L 27/01** (2013.01)

(58) **Field of Classification Search**  
CPC ..... H04L 25/03885; H04L 25/0212; H04L 27/01  
See application file for complete search history.

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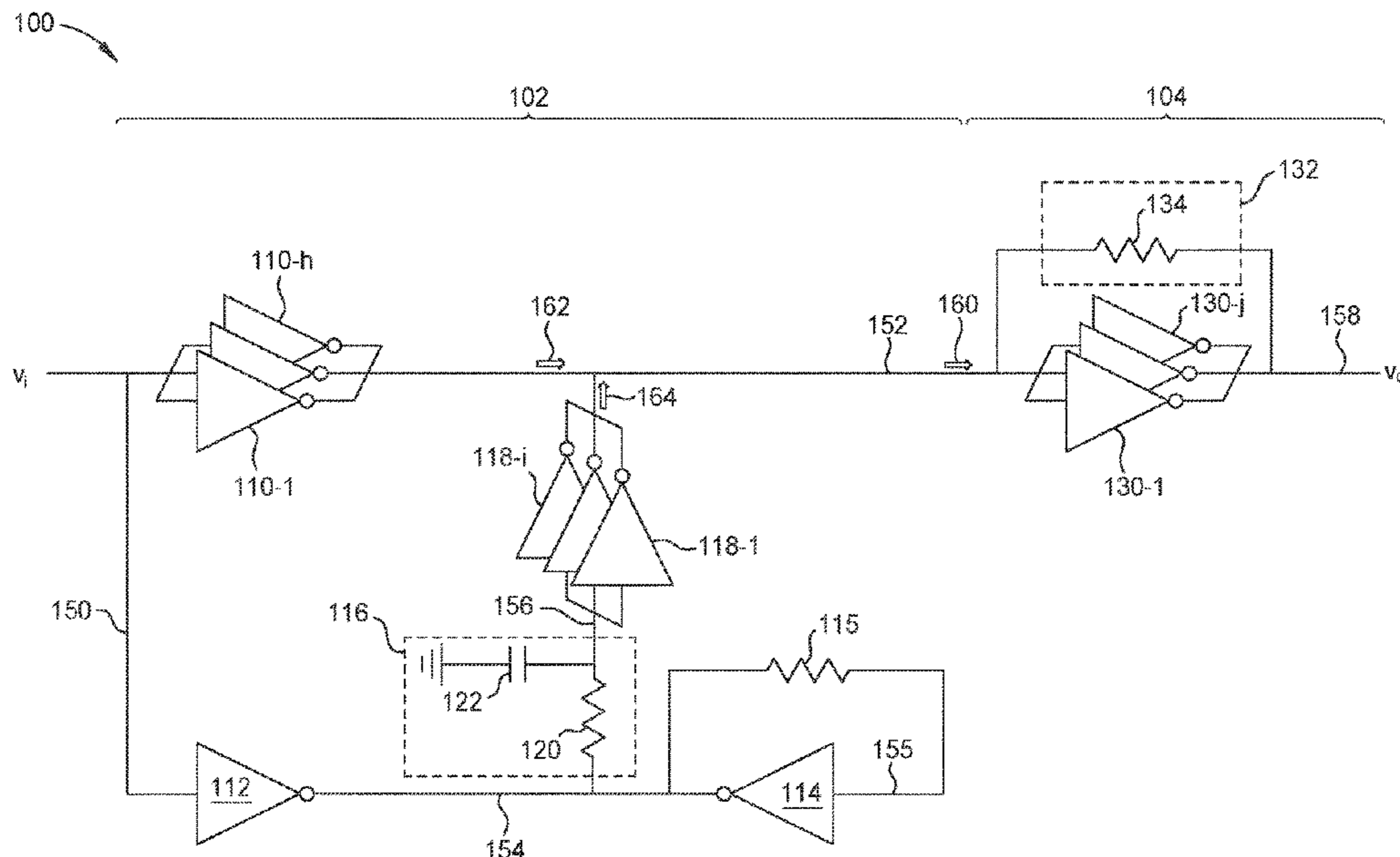
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(57) **ABSTRACT**

Some examples described herein provide for an integrated circuit including a continuous time linear equalizer (CTLE) circuit and a method of operating the integrated circuit. In an example, an integrated circuit includes a transconductance amplifier stage and a transimpedance amplifier stage. The transconductance amplifier stage has a first input node and a first output node. The transconductance amplifier stage includes a first complementary device inverter. The transimpedance amplifier stage has a second input node and a second output node. The first output node is electrically connected to the second input node. The transimpedance amplifier stage includes a second complementary device inverter.

**17 Claims, 12 Drawing Sheets**



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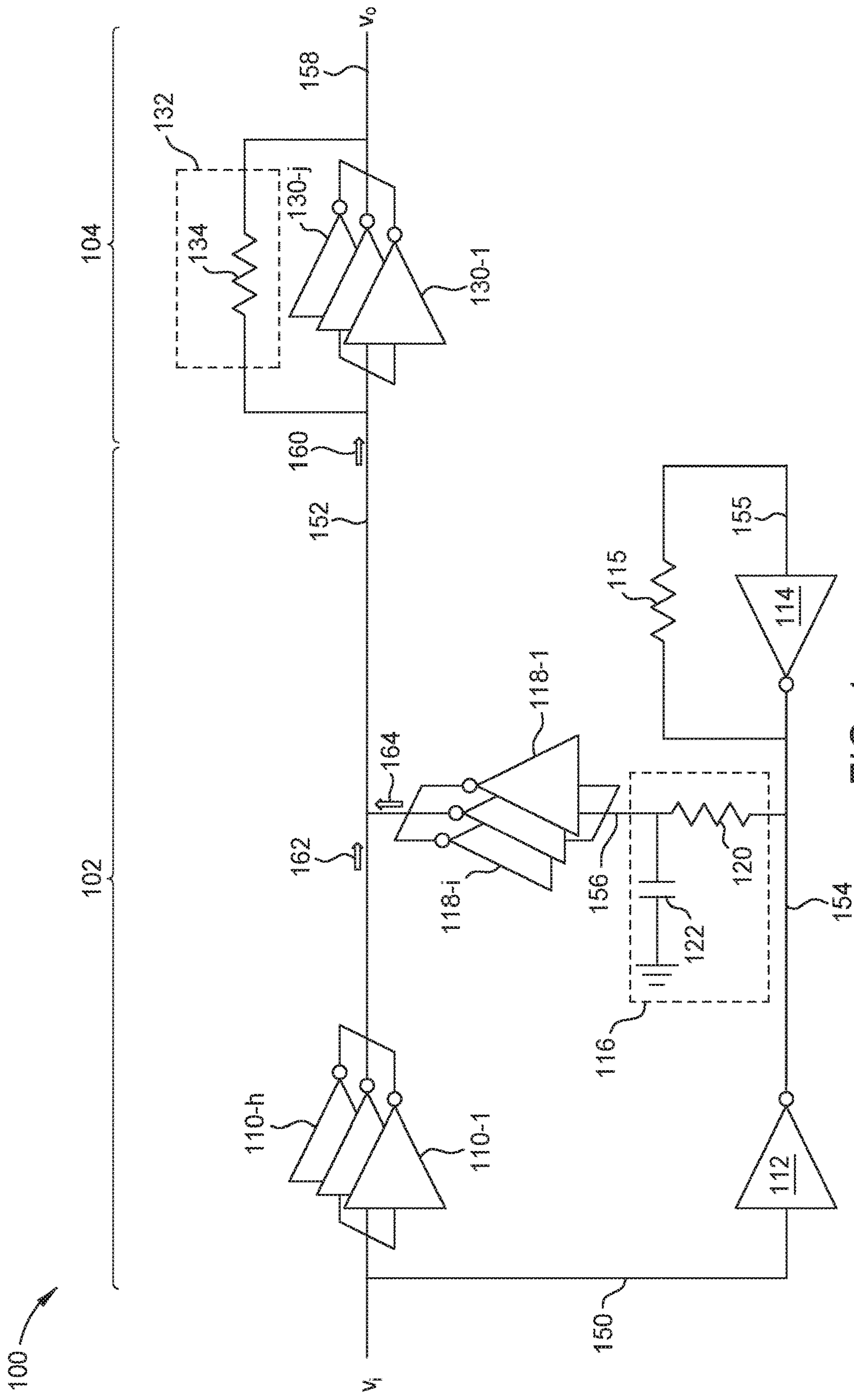


FIG. 1

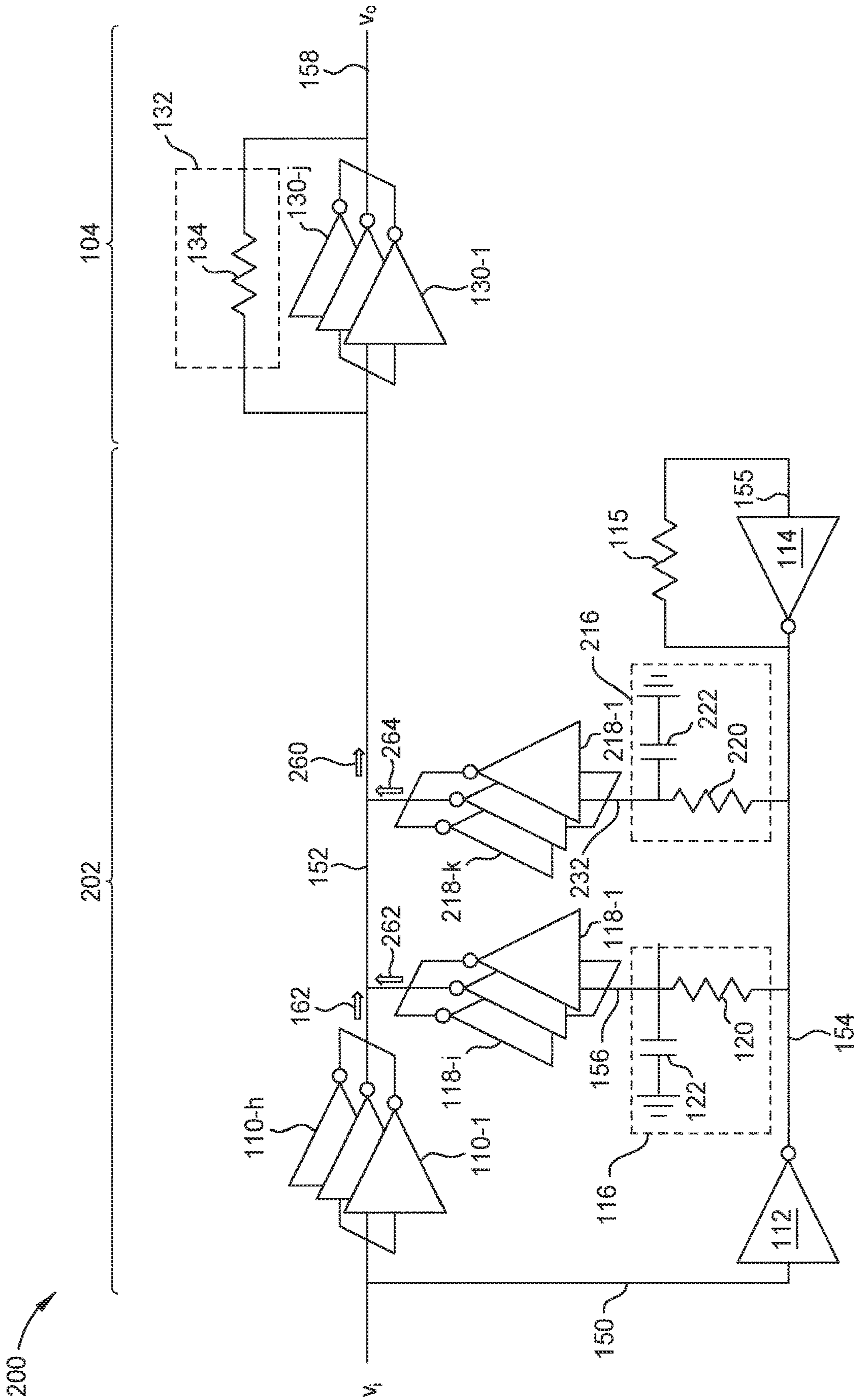


FIG. 2

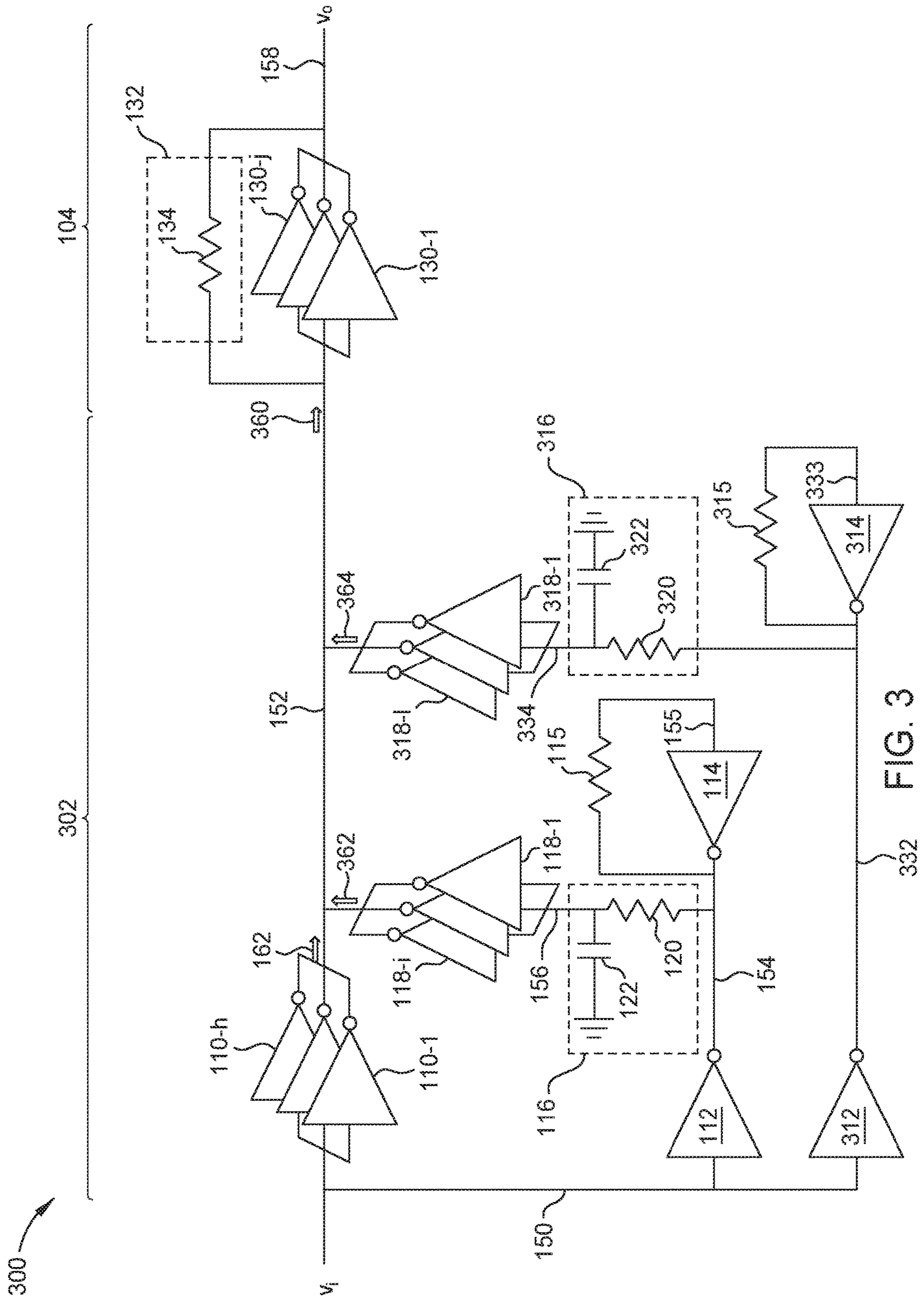


FIG. 3

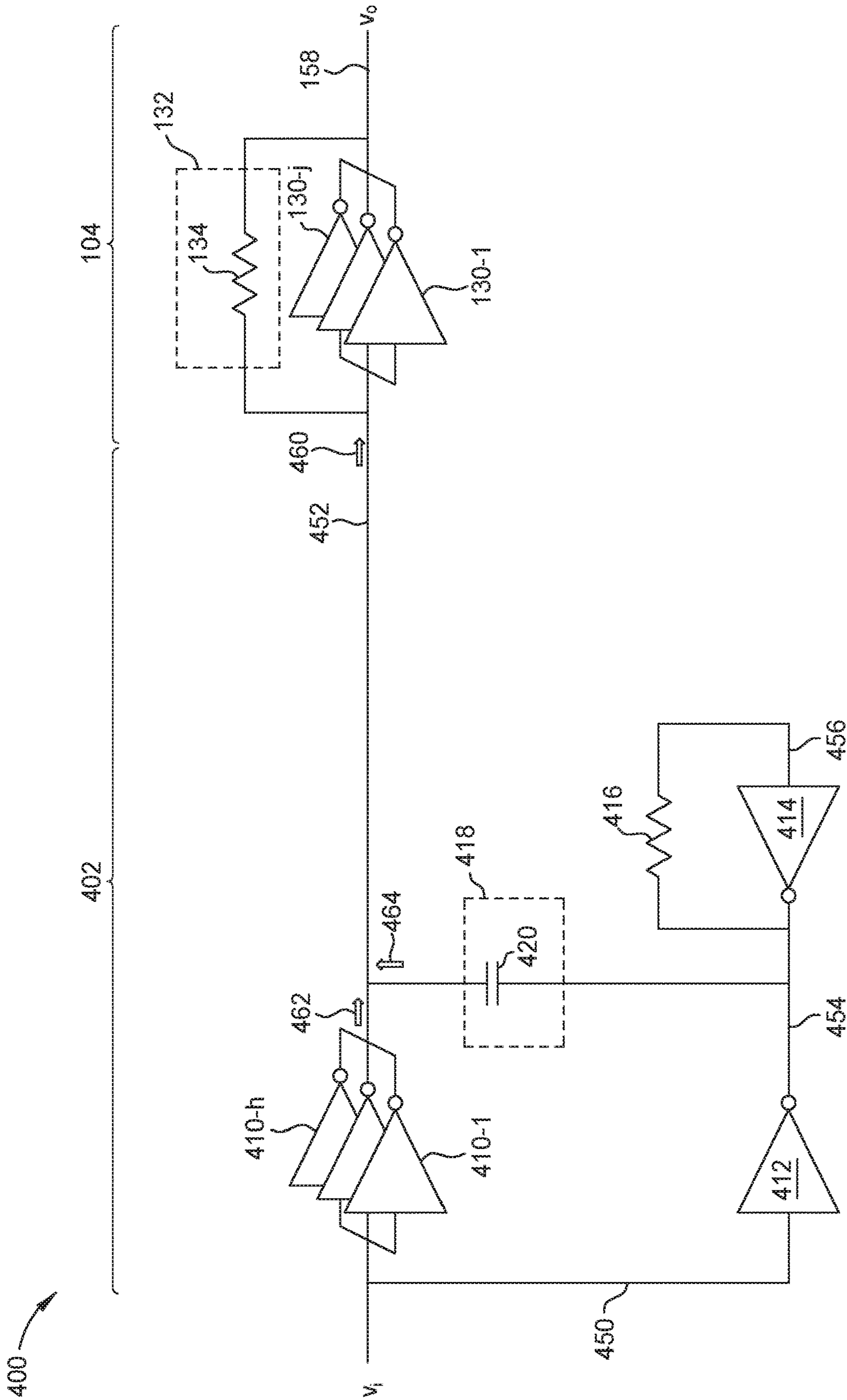


FIG. 4

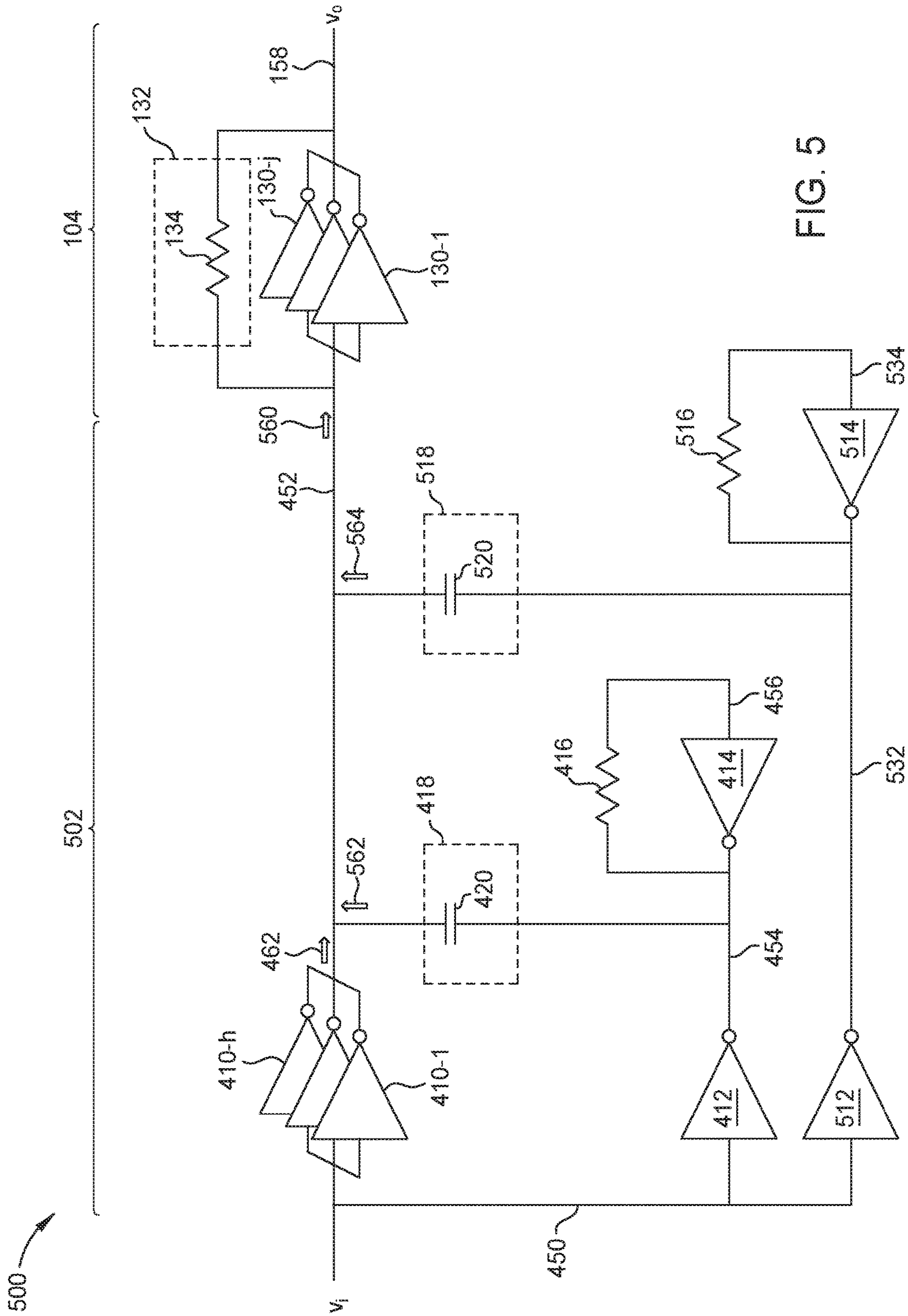


FIG. 5

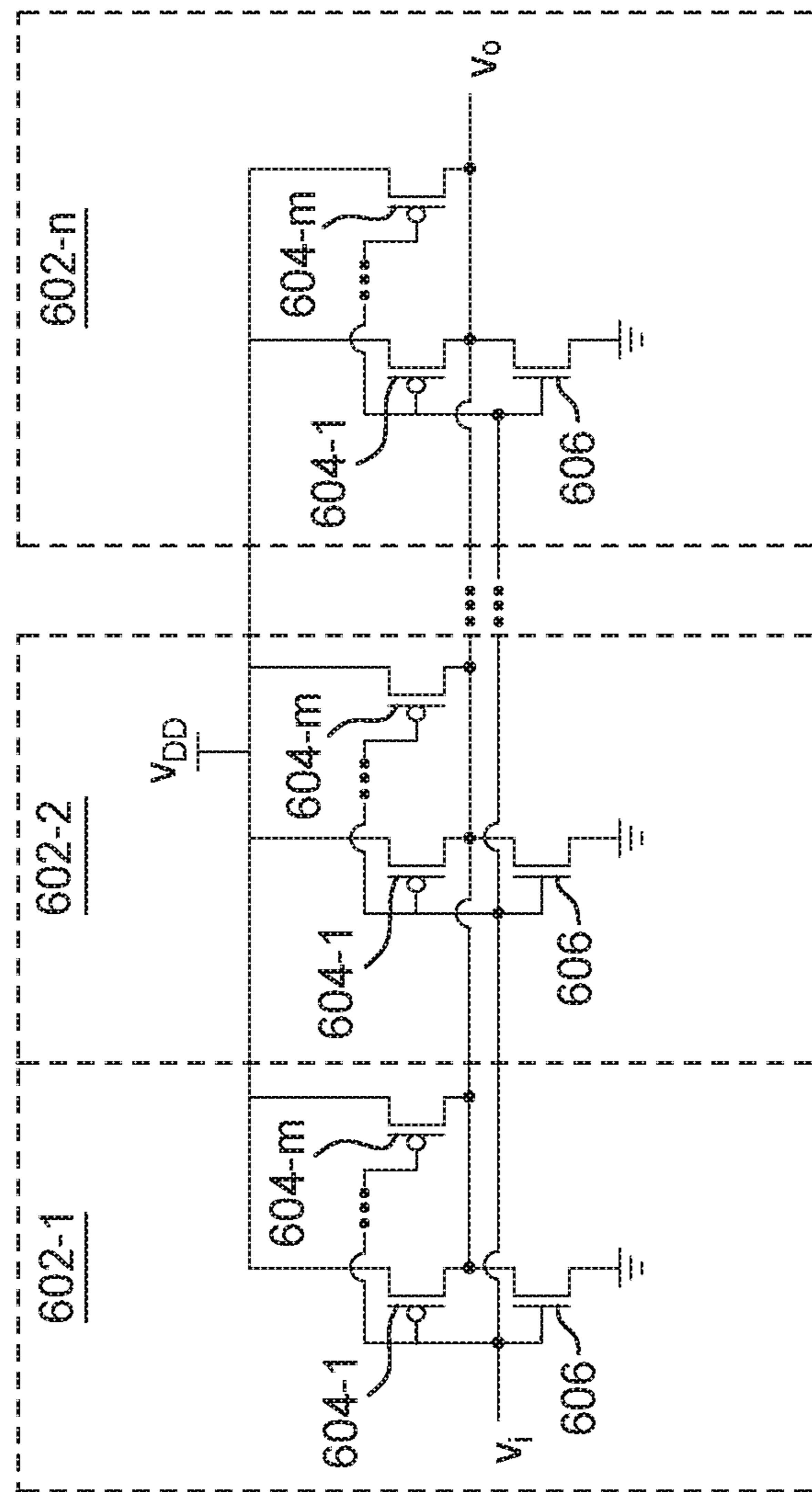


FIG. 6



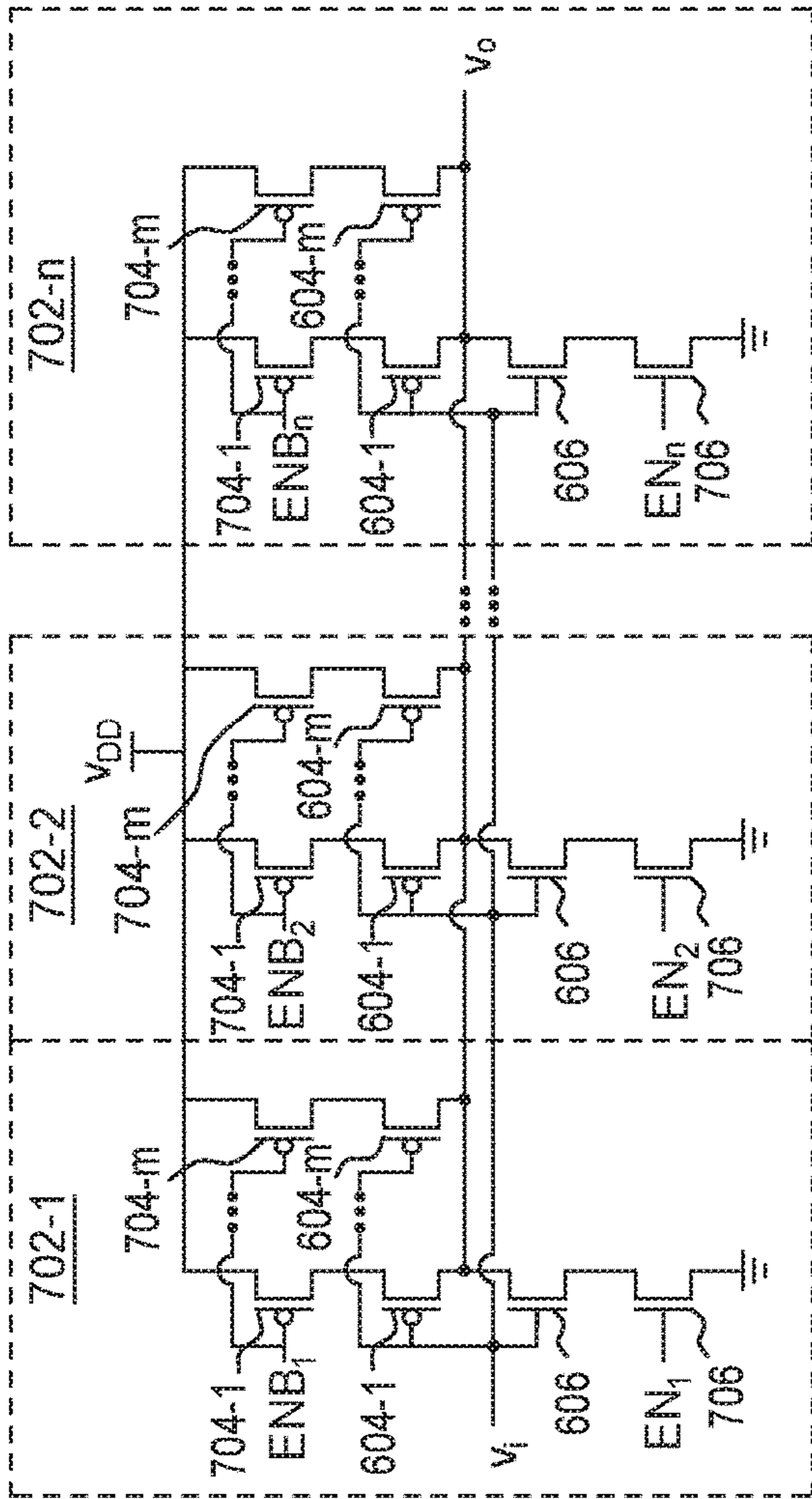


FIG. 7

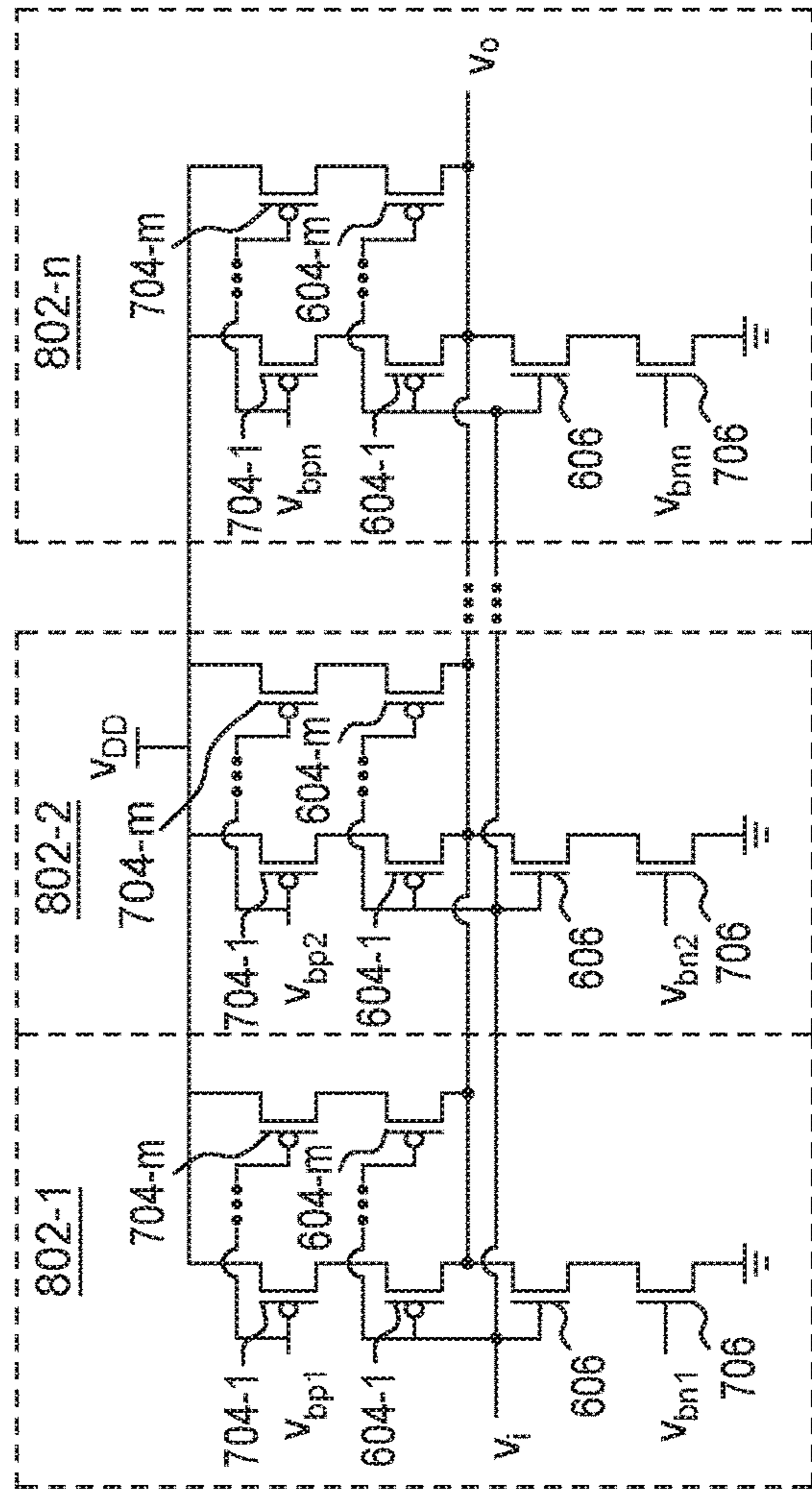


FIG. 8

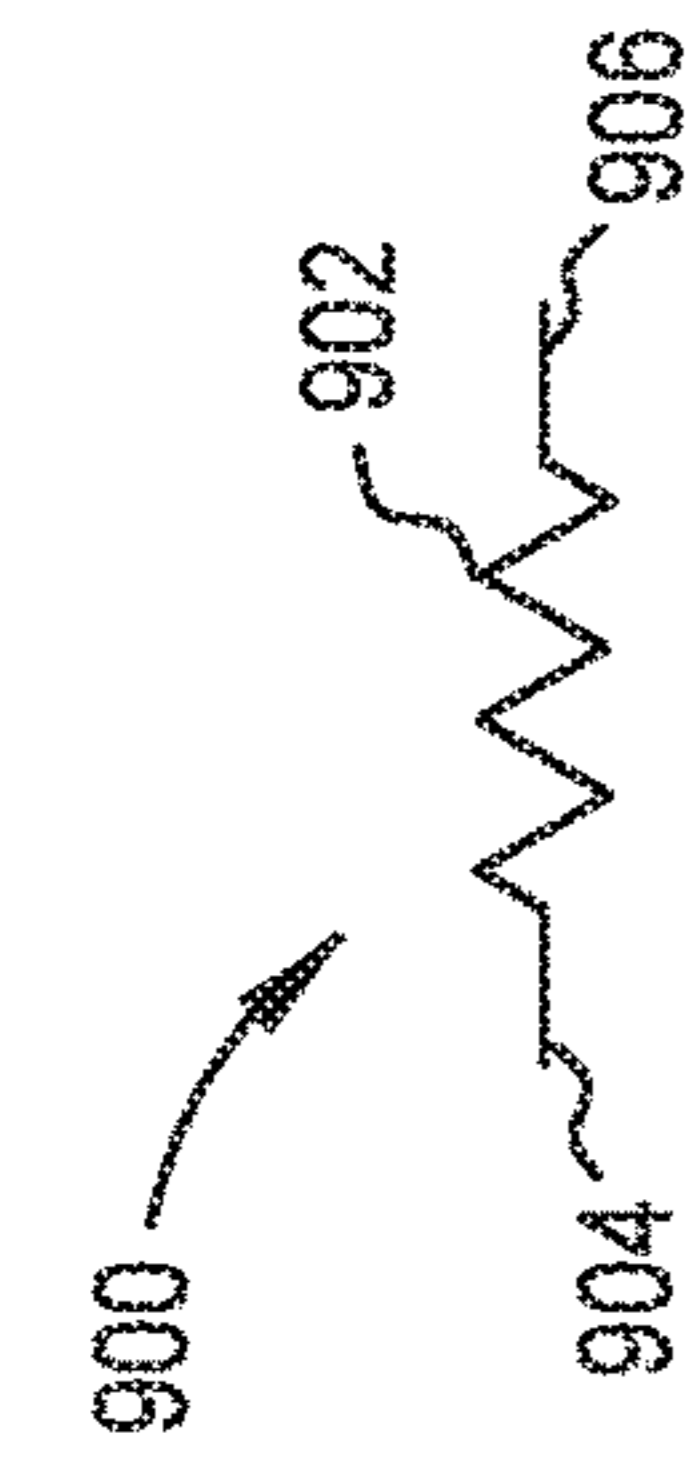


FIG. 9

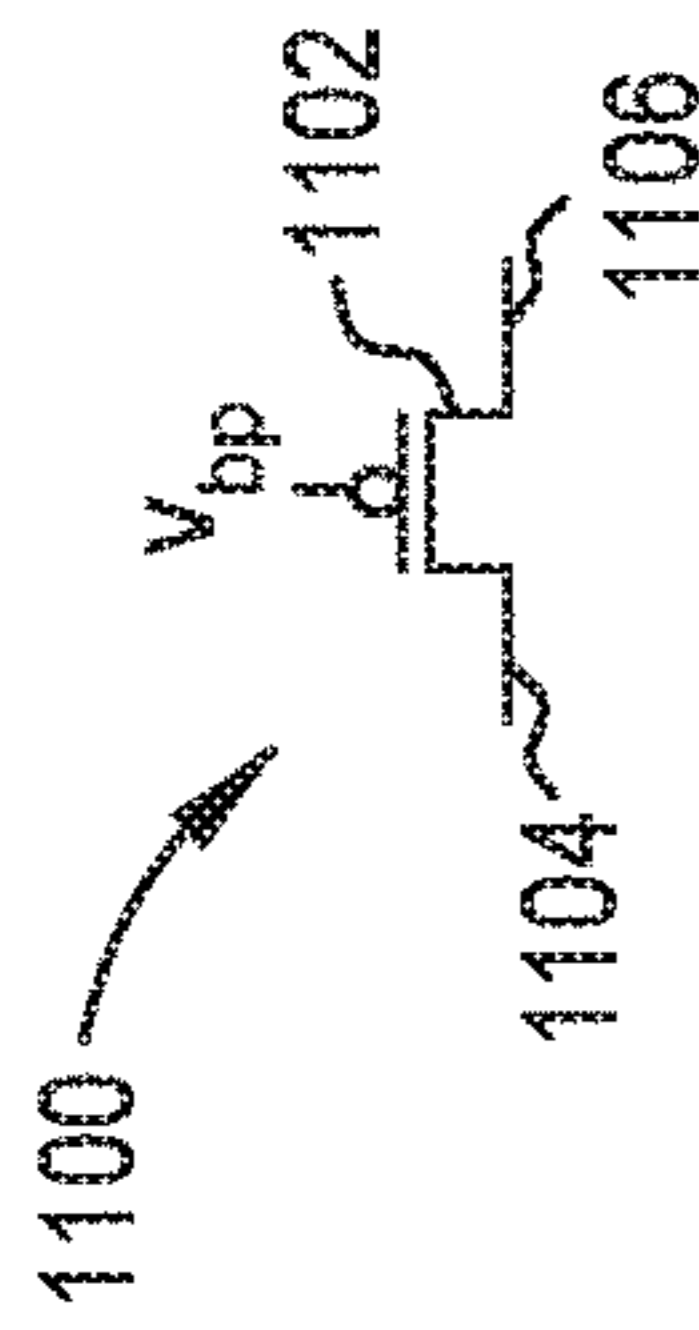


FIG. 11

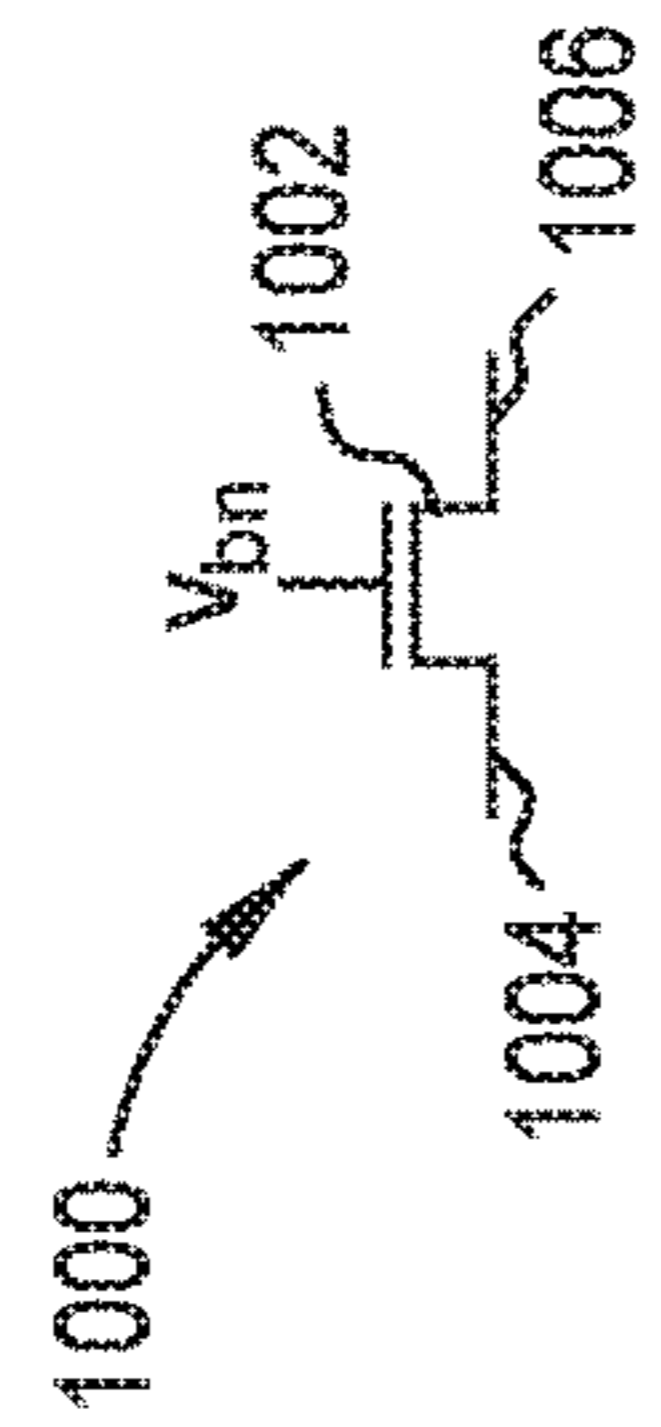


FIG. 10

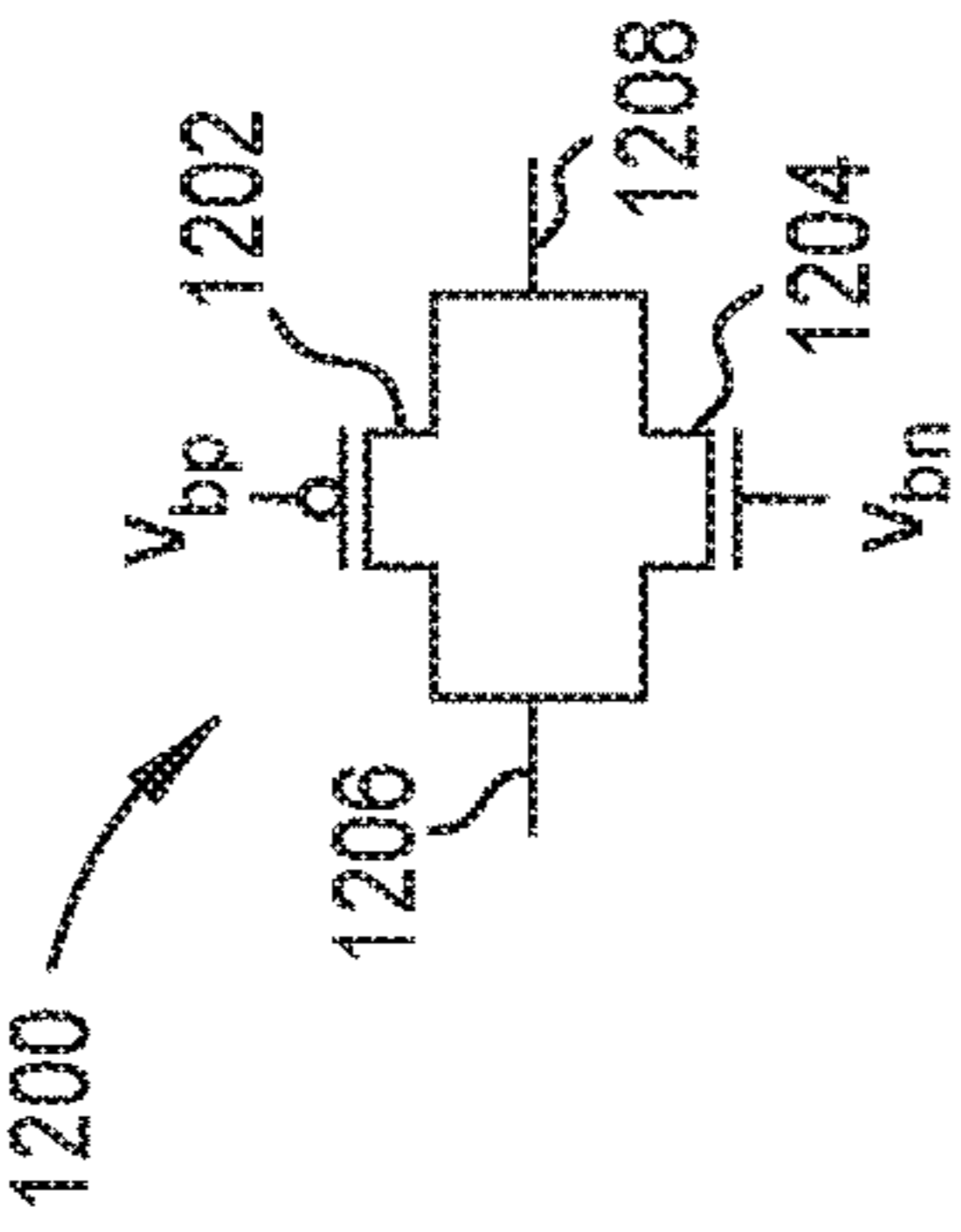


FIG. 12

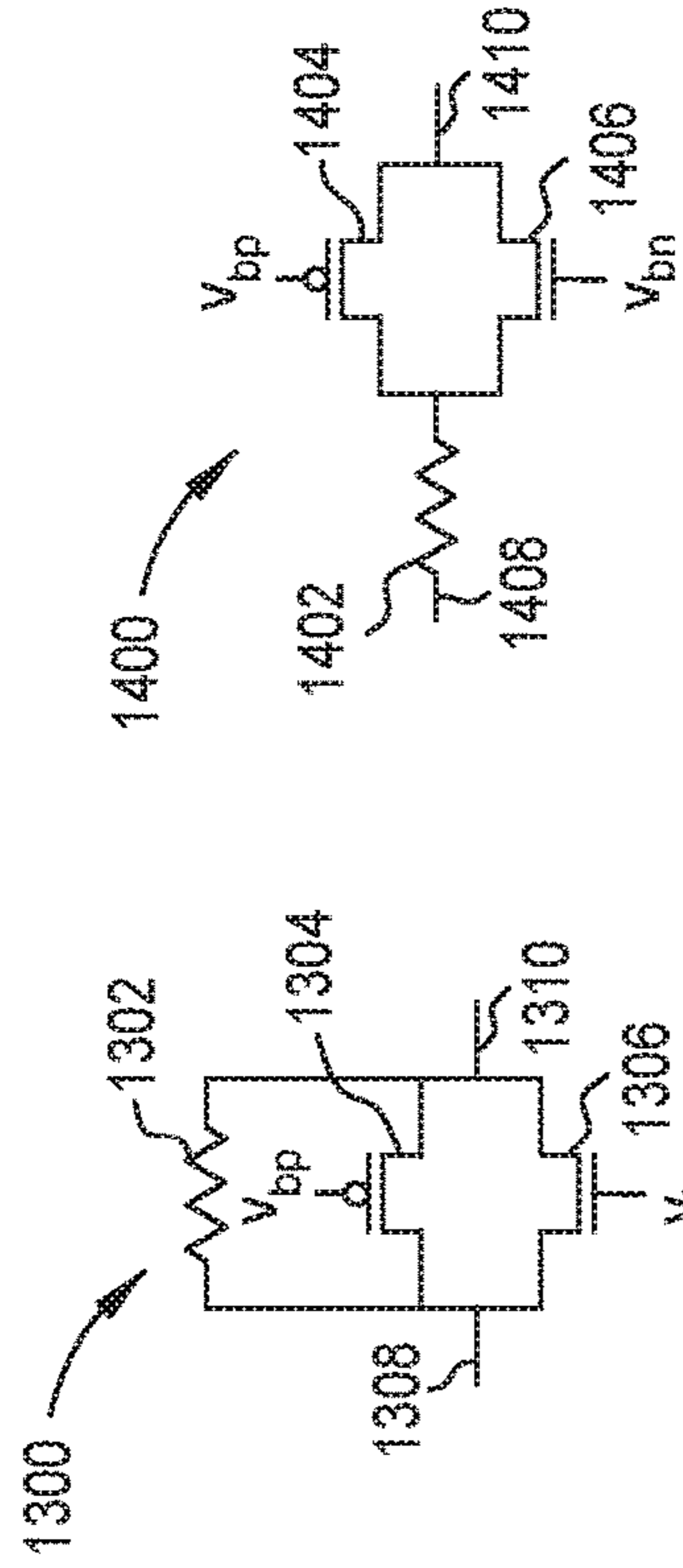


FIG. 13

FIG. 14

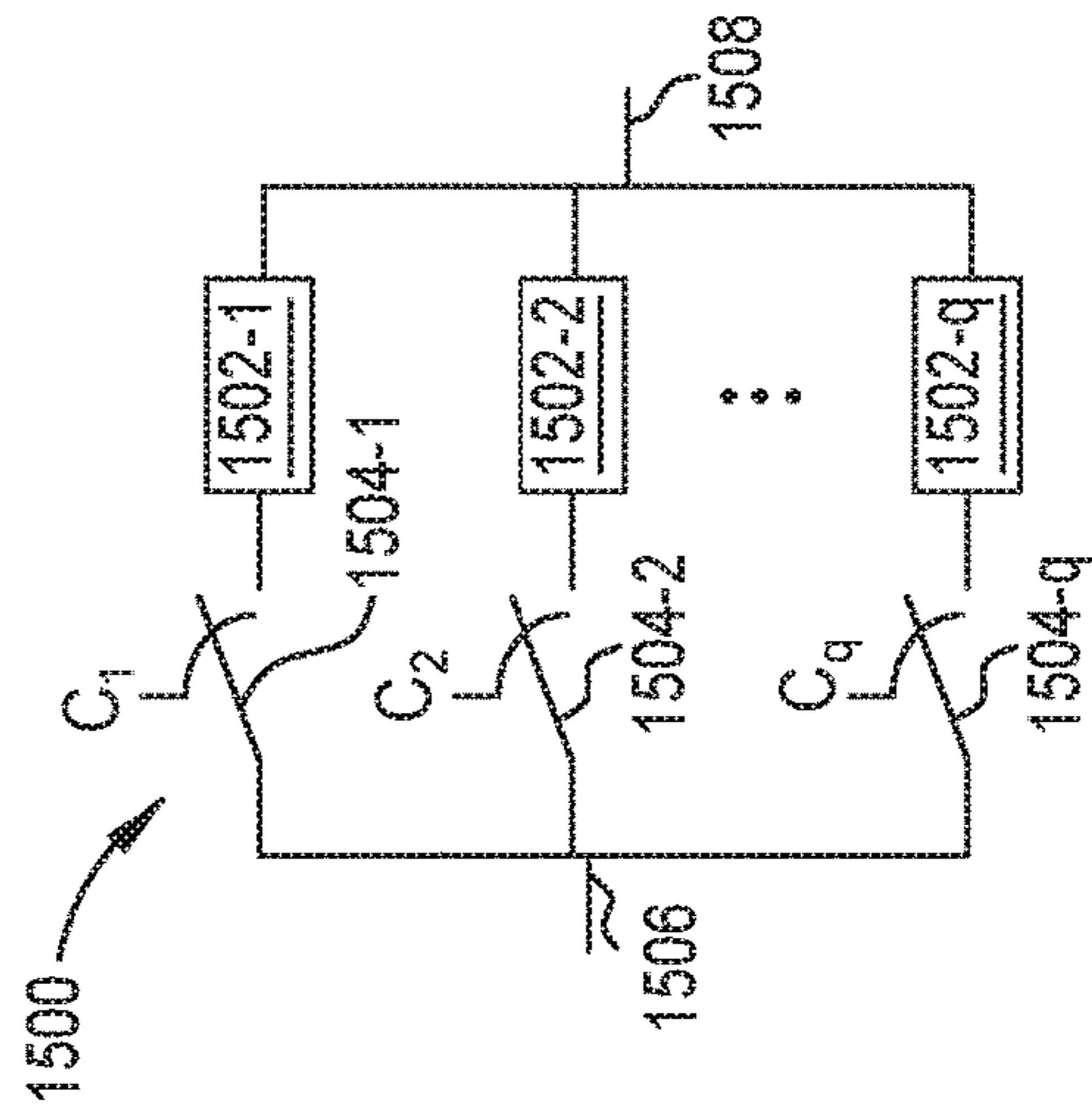


FIG. 15

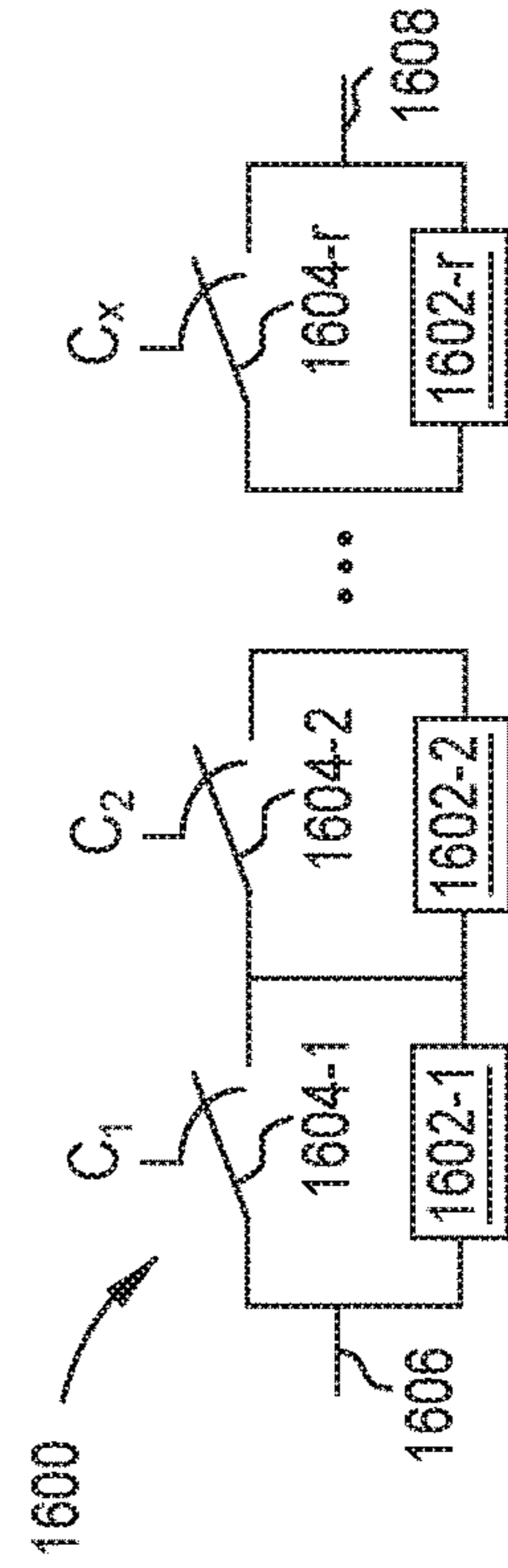


FIG. 16

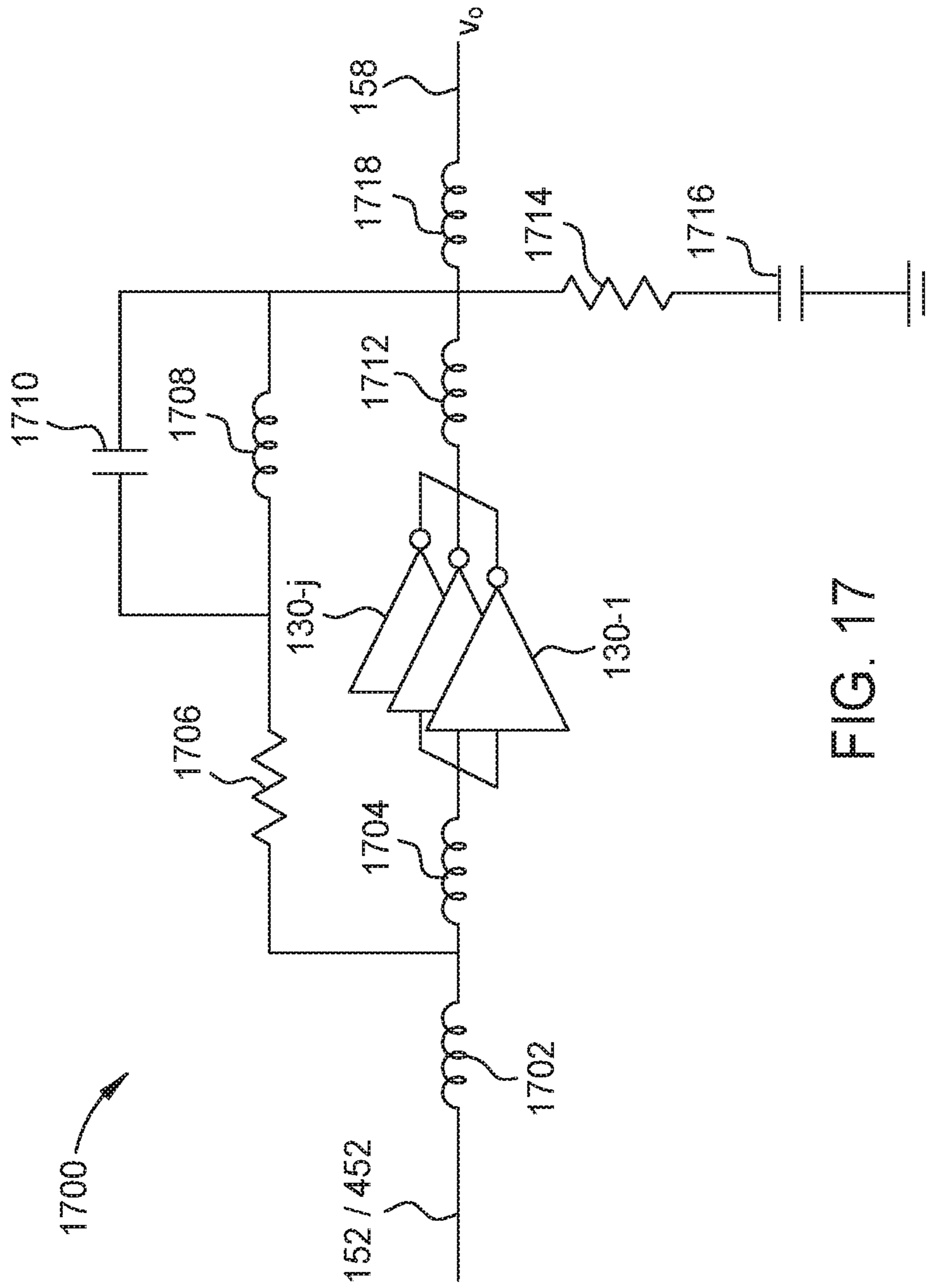


FIG. 17

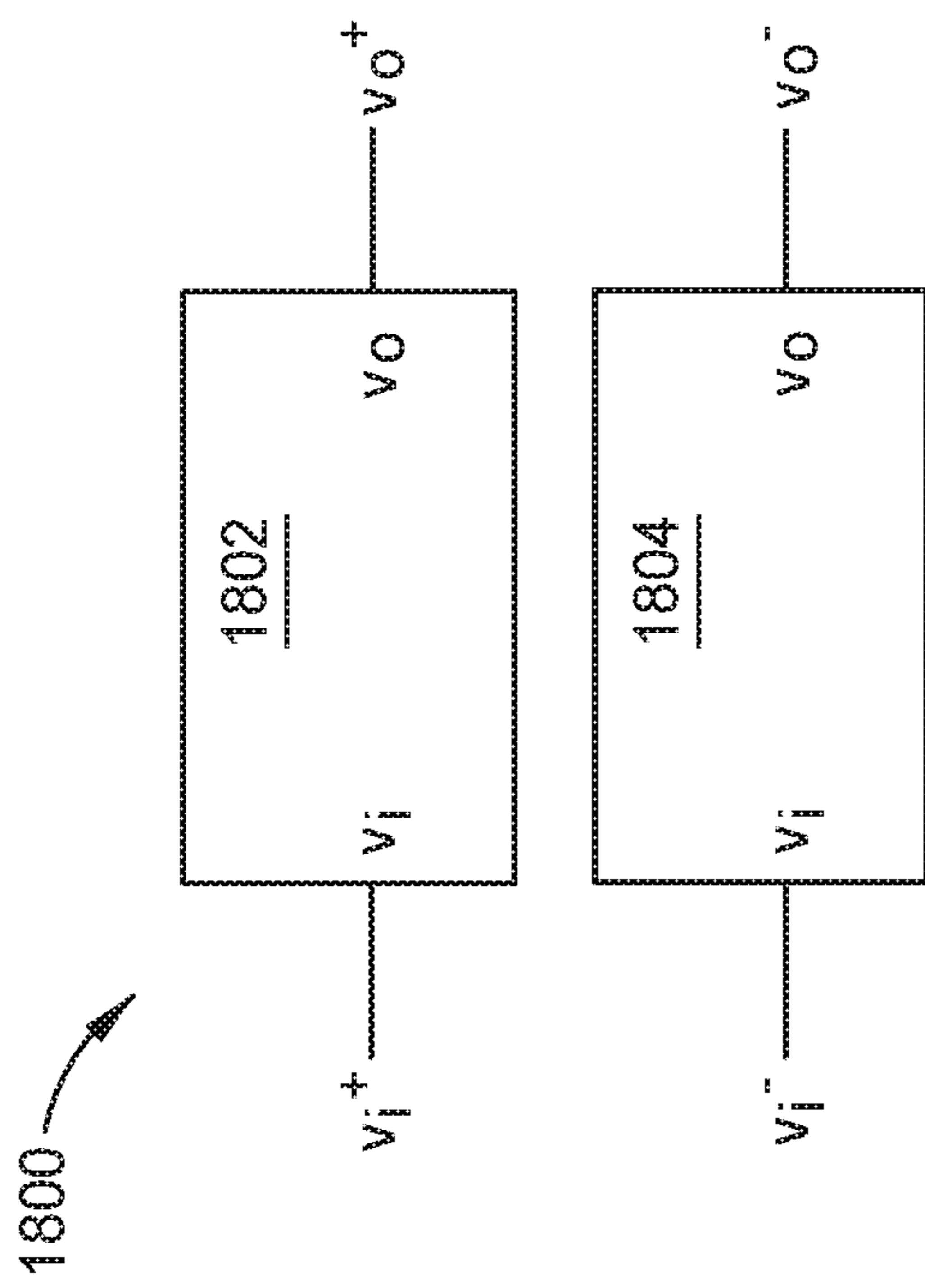


FIG. 18

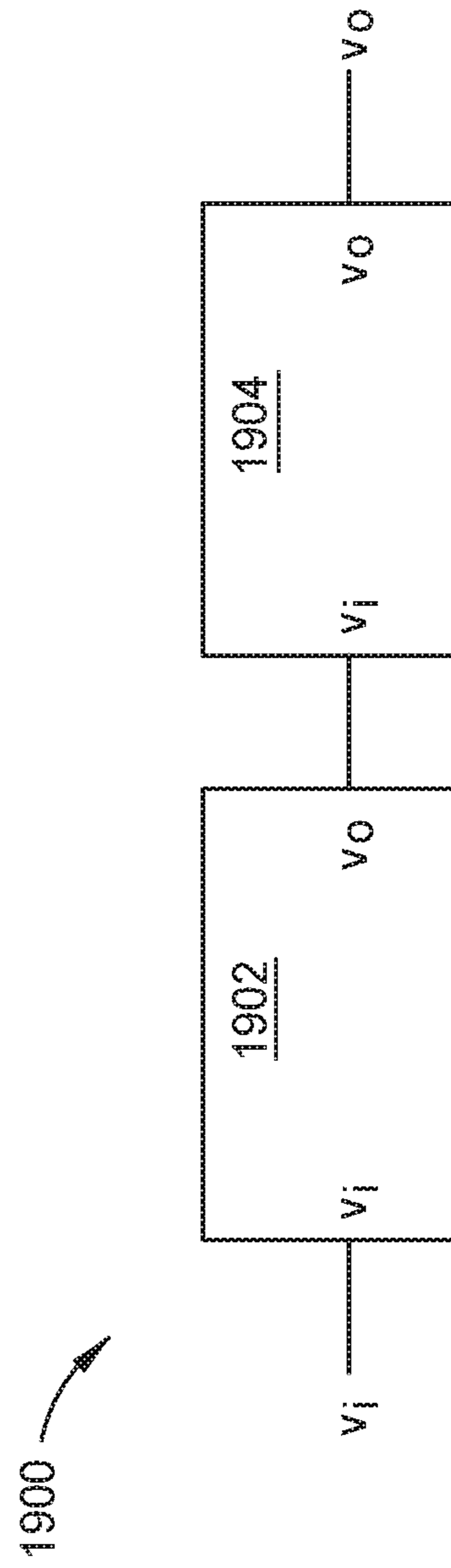


FIG. 19

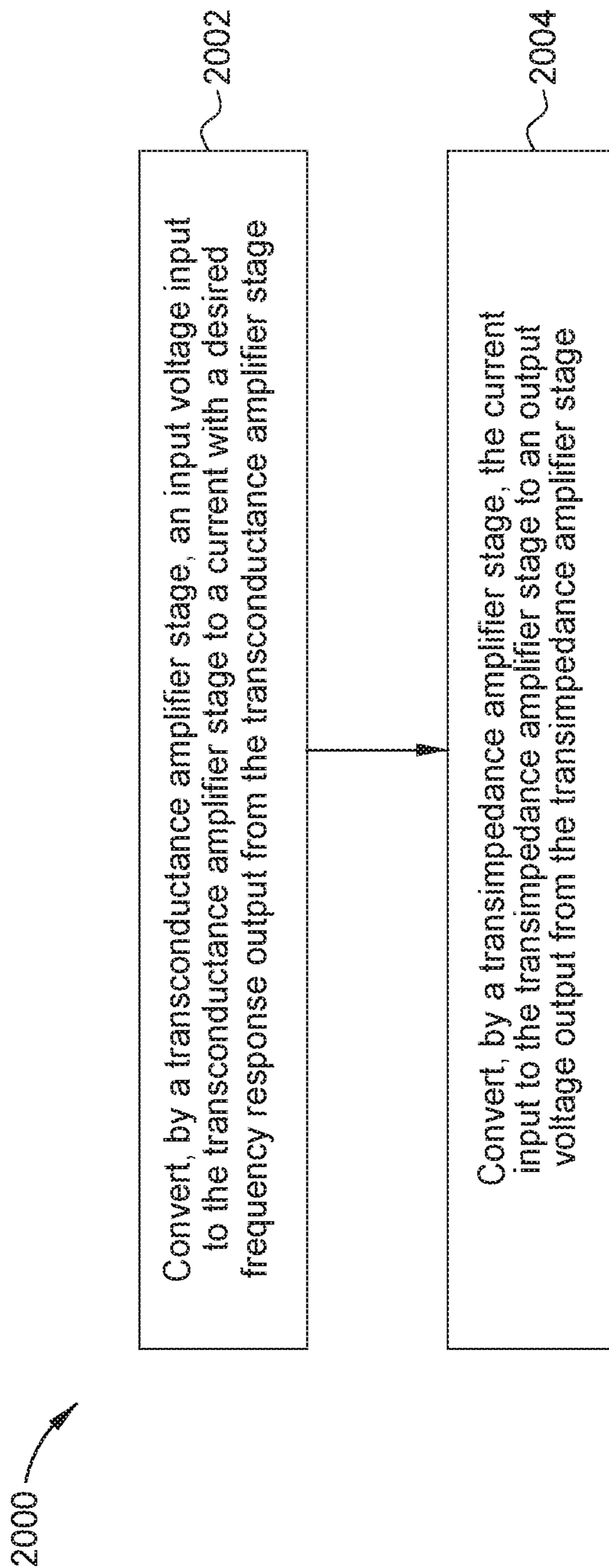


FIG. 20

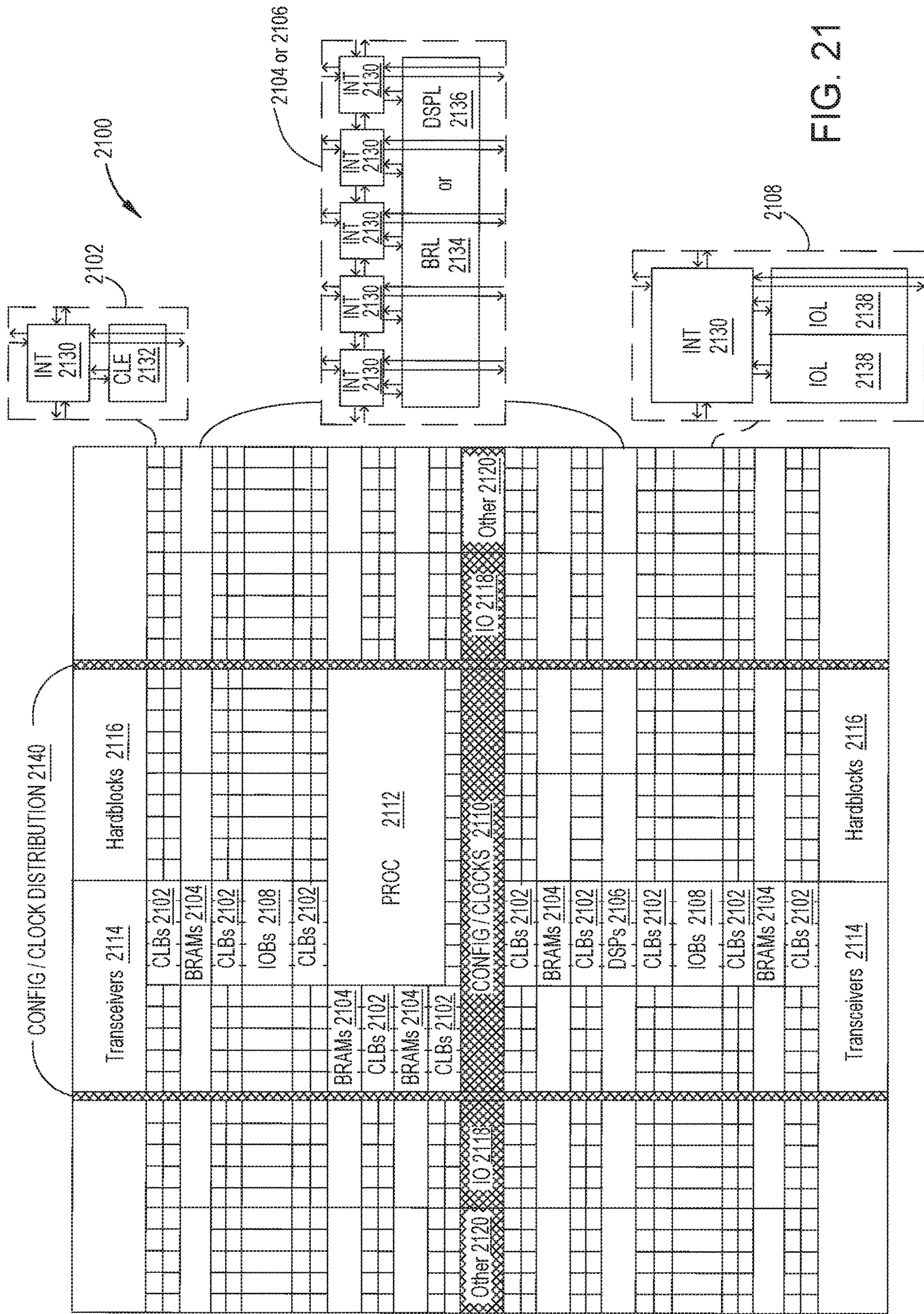


FIG. 21

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**INTEGRATED CIRCUIT INCLUDING A  
CONTINUOUS TIME LINEAR EQUALIZER  
(CTLE) CIRCUIT AND METHOD OF  
OPERATION**

TECHNICAL FIELD

Examples of the present disclosure generally relate to an integrated circuit including a continuous time linear equalizer (CTLE) circuit and a method of operating the integrated circuit.

BACKGROUND

High-speed serial communication can be an important function in many communication systems. A continuous time linear equalizer (CTLE) circuit may be implemented for high-speed serial link communications. A CTLE circuit can perform equalization by properly shaping magnitudes of signals at various frequencies. A communication channel can have a response based on the frequency of the signal communicated therethrough. For example, a communication channel can attenuate a signal at high frequencies. This frequency response of the communication channel may be a natural limitation of the communication channel. A CTLE circuit can accommodate the attenuation by increasing a magnitude of the signal (e.g., by increasing a gain of the CTLE circuit) at those high frequencies. A CTLE circuit is generally implemented to equalize a signal by creating a uniform frequency response (e.g., uniform gain) throughout a target frequency range from the source of the signal to the destination of the signal.

SUMMARY

Some examples described herein provide for an integrated circuit including a continuous time linear equalizer (CTLE) circuit and a method of operating the integrated circuit. Some CTLE circuits implemented as described herein can be compact, can operate at a low voltage, can be high speed, and/or can have a high bandwidth. Further, some examples implement CTLE circuits that are programmable, which can add a degree of flexibility.

An example of the present disclosure is an integrated circuit. The integrated circuit includes a first transconductance amplifier stage and a first transimpedance amplifier stage. The first transconductance amplifier stage has a first input node and a first output node. The first transconductance amplifier stage includes a first complementary device inverter. The first transimpedance amplifier stage has a second input node and a second output node. The first output node is electrically connected to the second input node. The first transimpedance amplifier stage includes a second complementary device inverter.

Another example of the present disclosure is an integrated circuit. The integrated circuit includes a continuous time linear equalizer circuit. The continuous time linear equalizer circuit includes a transconductance amplifier stage and a transimpedance amplifier stage. The transconductance amplifier stage has a first input node and a first output node. The transconductance amplifier stage includes a first path and a second path. The first path includes a first complementary device inverter electrically connected between the first input node and the first output node. The second path includes a second complementary device inverter and a first impedance circuit. The second complementary device inverter and the first impedance circuit are electrically

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connected between the first input node and the first output node. The transimpedance amplifier stage has a second input node and a second output node. The first output node is electrically connected to the second input node. The transimpedance amplifier stage includes a third complementary device inverter electrically connected between the second input node and the second output node.

Another example of the present disclosure is a method for operating an integrated circuit. An input voltage input to a transconductance amplifier stage is converted, by the transconductance amplifier stage, to a current output from the transconductance amplifier stage. The transconductance amplifier stage includes a first complementary device inverter. The current, which is input to a transimpedance amplifier stage, is converted, by the transimpedance amplifier stage, to an output voltage output from the transimpedance amplifier stage. The transimpedance amplifier stage includes a second complementary device inverter.

These and other aspects may be understood with reference to the following detailed description.

BRIEF DESCRIPTION OF THE DRAWINGS

So that the manner in which the above-recited features can be understood in detail, a more particular description, briefly summarized above, may be had by reference to example implementations, some of which are illustrated in the appended drawings. It is to be noted, however, that the appended drawings illustrate only typical example implementations and are therefore not to be considered limiting of its scope.

FIG. 1 is a circuit schematic of a continuous time linear equalizer (CTLE) circuit according to some examples.

FIG. 2 is a circuit schematic of another CTLE circuit according to some examples.

FIG. 3 is a circuit schematic of another CTLE circuit according to some examples.

FIG. 4 is a circuit schematic of another CTLE circuit according to some examples.

FIG. 5 is a circuit schematic of another CTLE circuit according to some examples.

FIG. 6 is a circuit schematic of a number of parallel-connected complementary device inverters according to some examples.

FIG. 7 is a circuit schematic of a number of parallel-connected complementary device inverters according to some examples.

FIG. 8 is a circuit schematic of a number of parallel-connected complementary device inverters according to some examples.

FIGS. 9, 10, 11, 12, 13, and 14 are circuit schematics of example resistive elements according to some examples.

FIGS. 15 and 16 are circuit schematics of impedance arrays according to some examples.

FIG. 17 is a circuit schematic of a transimpedance amplifier stage according to some examples.

FIG. 18 is a schematic of a pseudo differential CTLE circuit according to some examples.

FIG. 19 is a schematic of cascaded CTLE circuits according to some examples.

FIG. 20 is a flowchart of an operation of a CTLE circuit according to some examples.

FIG. 21 illustrates a field programmable gate array (FPGA) that may be implemented as a programmable device according to some examples.

To facilitate understanding, identical reference numerals have been used, where possible, to designate identical

elements that are common to the figures. It is contemplated that elements of one example may be beneficially incorporated in other examples.

#### DETAILED DESCRIPTION

Some examples described herein provide for an integrated circuit including a continuous time linear equalizer (CTLE) circuit and a method of operating the integrated circuit. In some examples, a CTLE circuit includes a transconductance amplifier stage and a transimpedance amplifier stage. The transconductance amplifier stage and the transimpedance amplifier stage can be serially connected. The transconductance amplifier stage and the transimpedance amplifier stage can each include one or more complementary device inverters (e.g., complementary metal-oxide-semiconductor (CMOS) inverters). Some CTLE circuits implemented as described herein can be compact, can operate at a low voltage, can be high speed, and/or can have a high bandwidth. Further, some examples implement CTLE circuits that are programmable, which can add a degree of flexibility.

Various features are described hereinafter with reference to the figures. It should be noted that the figures may or may not be drawn to scale and that the elements of similar structures or functions are represented by like reference numerals throughout the figures. It should be noted that the figures are only intended to facilitate the description of the features. They are not intended as an exhaustive description of the claimed invention or as a limitation on the scope of the claimed invention. In addition, an illustrated example need not have all the aspects or advantages shown. An aspect or an advantage described in conjunction with a particular example is not necessarily limited to that example and can be practiced in any other examples even if not so illustrated or if not so explicitly described. Further, methods described herein may be described in a particular order of operations, but other methods according to other examples may be implemented in various other orders (e.g., including different serial or parallel performance of various operations) with more or fewer operations.

In the description that follows, various signals (e.g., voltages and/or currents) are described in the context of the operation of various circuits. A described signal indicates a corresponding node on which the signal is propagated and further indicates nodes that are communicatively coupled and/or electrically connected. For example, description of a signal output from a first circuit and input to a second circuit indicates an output node of the first circuit (on which the signal is output from the first circuit) is communicatively coupled and/or electrically connected to an input node of the second circuit (on which the signal is input to the second circuit). Explicit description of such nodes may be omitted in the following description, but a person having ordinary skill in the art will readily understand the presence of the nodes.

FIG. 1 is a circuit schematic of a continuous time linear equalizer (CTLE) circuit 100 according to some examples. The CTLE circuit 100 includes a transconductance amplifier (GM) stage 102 and a transimpedance amplifier (TIA) stage 104.

The transconductance amplifier stage 102 includes a primary path and a feed forward path. The transconductance amplifier stage 102 includes one or more inverters 110-1 to 110-*h* (collectively or individually, inverter(s) 110) in the primary path, and includes an inverter 112, an inverter 114, a resistor 115, an impedance circuit 116, and one or more inverters 118-1 to 118-*i* (collectively or individually,

inverter(s) 118) in the feed forward path. The impedance circuit 116 includes a resistor 120 and a capacitor 122 as a simple example. The transimpedance amplifier stage 104 includes one or more inverters 130-1 to 130-*j* (collectively or individually, inverter(s) 130) and an impedance circuit 132. The impedance circuit 132 includes a resistor 134 as a simple example.

Each inverter 110 (whether one is implemented or multiple are implemented) has an input node electrically connected to an input voltage ( $v_i$ ) node 150 and has an output node electrically connected to an intermediate node 152. The input voltage ( $v_i$ ) node 150 can function as an input node of the transconductance amplifier stage 102. If multiple inverters 110 are implemented, the inverters 110 are electrically connected in parallel. The intermediate node 152 can be an output node of the transconductance amplifier stage 102 and an input node of the transimpedance amplifier stage 104.

The inverter 112 has an input node electrically connected to the input voltage ( $v_i$ ) node 150 and has an output node electrically connected to a first feed forward path node 154. In the illustrated example, the inverter 114 has an output node electrically connected to the first feed forward path node 154, and a first terminal of the resistor 115 is electrically connected to the first feed forward path node 154. A second terminal of the resistor 115 (opposite from the first terminal) is electrically connected to an input node 155 of the inverter 114. In some examples, the resistor 115 can be omitted, and the input node and output node of the inverter 114 can each be electrically connected to the first feed forward path node 154. The impedance circuit 116 has a first terminal electrically connected to the first feed forward path node 154. Hence, in the illustrated example, the output node of the inverter 112, the output node of the inverter 114, the first terminal of the resistor 115, and the first terminal of the impedance circuit 116 are electrically connected together at the first feed forward path node 154.

A second terminal of the impedance circuit 116 is electrically connected to a second feed forward path node 156. In the illustrated example, the resistor 120 has a first terminal that is the first terminal of the impedance circuit 116, which is electrically connected to the first feed forward path node 154. A second terminal of the resistor 120 (opposite from the first terminal of the resistor 120) is electrically connected to a first terminal of the capacitor 122, which together form the second terminal of the impedance circuit 116 that is electrically connected to the second feed forward path node 156. A second terminal of the capacitor 122 (opposite from the first terminal of the capacitor 122) is electrically connected to a ground node. The resistor 120 and capacitor 122 are shown for illustration purposes. Any impedance circuit can be implemented to obtain a desired frequency response. In some examples, the impedance circuit 116 can include a combination of a number of resistors, a number of capacitors, and/or a number of inductors. Any impedance, such as a result of the resistance of the resistor 120 and/or capacitance of the capacitor 122, can be and/or include an explicitly formed component in the circuit, or can be and/or include a parasitic impedance in the circuit.

The second feed forward path node 156 is further electrically connected to respective input nodes of the one or more inverters 118. Respective output nodes of the one or more inverters 118 are electrically connected to the intermediate node 152. Hence, if multiple inverters 118 are implemented, the inverters 118 are electrically connected in parallel.

In the transimpedance amplifier stage 104, each inverter 130 (whether one is implemented or multiple are imple-



mented) has an input node electrically connected to the intermediate node **152** and has an output node electrically connected to an output voltage ( $v_o$ ) node **158**. The output voltage ( $v_o$ ) node **158** can function as an output node of the transimpedance amplifier stage **104**, and hence, as an output node of the CTLE circuit **100**. If multiple inverters **130** are implemented, the inverters **130** are electrically connected in parallel.

A first terminal of the impedance circuit **132** is electrically connected to the intermediate node **152**. A second terminal of the impedance circuit **132** is electrically connected to the output voltage ( $v_o$ ) node **158**. In the illustrated example, the resistor **134** has a first terminal that is the first terminal of the impedance circuit **132**, which is electrically connected to the intermediate node **152**. A second terminal of the resistor **134** (opposite from the first terminal of the resistor **134**) is the second terminal of the impedance circuit **132** and is electrically connected to the output voltage ( $v_o$ ) node **158**. The resistor **134** is shown for illustration purposes. Any impedance circuit can be implemented to obtain a desired frequency response. In some examples, the impedance circuit **132** can include a combination of a number of resistors, a number of capacitors, and/or a number of inductors. In some examples, the impedance circuit **132** can include any of those components, such as a capacitor, electrically connected between the output voltage ( $v_o$ ) node **158** and a ground node. Any impedance can be and/or include an explicitly formed component in the circuit, or can be and/or include a parasitic impedance in the circuit.

In some examples, any or each of the inverters **110**, **112**, **114**, **118** are complementary device inverters, such as CMOS inverters. In some examples, any or each of the inverters **130** are complementary device inverters, such as CMOS inverters.

In some examples, any or each of the components of the CTLE circuit **100** are programmable. Programmability of any component can be implemented by a device, like a switch such as a transistor, that selectively electrically connects the respective component in the CTLE circuit **100**, and/or can be implemented by tuning or biasing the respective component to implement a desired frequency response and/or have a desired electrical characteristic (e.g., response, impedance, conductance, etc.). Various examples of programmable components are described below. Programmability of any component(s) can permit the CTLE circuit **100** to be dynamically tunable to achieve a desired frequency response.

In operation, the transconductance amplifier stage **102** converts an input voltage ( $v_i$ ) on the input voltage ( $v_i$ ) node **150** to a current **160** that is output from the transconductance amplifier stage **102** and input into the transimpedance amplifier stage **104**. The transimpedance amplifier stage **104** converts the current **160** to an output voltage ( $v_o$ ) output on the output voltage ( $v_o$ ) node **158**. The primary path of the transconductance amplifier stage **102** converts the input voltage ( $v_i$ ) on the input voltage ( $v_i$ ) node **150** to a primary path current **162**, and the feed forward path of the transconductance amplifier stage **102** converts the input voltage ( $v_i$ ) on the input voltage ( $v_i$ ) node **150** to a feed forward path current **164**. The primary path current **162** and the feed forward path current **164** sum to form the current **160**.

The feed forward path is configured such that the magnitude of the feed forward path current **164** from the feed forward path is subtracted from the primary path current **162** from the primary path. Hence, the transconductance amplifier stage **102** may be referred to as having subtractive feed forward. In the illustrated example, the impedance circuit

**116** is configured as a low-pass filter. Hence, in the illustrated example and assuming a same magnitude of an input voltage ( $v_i$ ) across relevant frequencies, the magnitude of the feed forward path current **164** can generally be greater at lower frequencies (e.g., from DC (e.g., 0 Hz) to the 3 dB roll off frequency of the impedance circuit **116**) and can generally be lower at higher frequencies (e.g., greater than the 3 dB roll off frequency of the impedance circuit **116**). Accordingly, in such example, the feed forward path can cause a greater magnitude of current to be subtracted from the primary path current **162** at lower frequencies to generate the current **160**, while causing a lower magnitude of current to be subtracted from the primary path current **162** at higher frequencies. In such examples, a magnitude of the current **160** can be lower at low frequencies and higher at high frequencies, which can cause peaking of the current **160** at higher frequencies. Generally, the gain of the frequency response of the transconductance amplifier stage **102** in this example can be greater at higher frequencies (e.g., peak at those higher frequencies) and can be lower at lower frequencies.

The frequency responses of the inverters **110**, **112**, **114**, **118** can also affect the current **160**. In various examples, the frequency response of the impedance circuit **116** can dominate the frequency response of the transconductance amplifier stage **102**, while in other examples, one or more of the inverters **110**, **112**, **114**, **118** can dominate the frequency response of the transconductance amplifier stage **102**. In further examples, both the inverters **110**, **112**, **114**, **118** and the impedance circuit **116** can be significant contributors to the frequency response. The programmability of any of the inverters **110**, **112**, **114**, **118** can be used to implement different frequency responses of the respective inverter(s). Additionally, any other circuit configuration can be implemented for the impedance circuit **116** to achieve a desired frequency response. In some examples, the impedance circuit **116** can be configured as or including a low-pass filter, a high-pass filter, a notch filter, a band-pass filter, or the like. Any filter can have any combination of poles and/or zeros in its transfer function.

FIG. 2 is a circuit schematic of another CTLE circuit **200** according to some examples. The CTLE circuit **200** includes a transconductance amplifier stage **202** and the transimpedance amplifier stage **104**. The transconductance amplifier stage **202** of FIG. 2 is similar to the transconductance amplifier stage **102** of FIG. 1 but with forked branches in the feed forward path. Two branches in the feed forward path are illustrated in FIG. 2 and described below. In other examples, any number of branches can be implemented in a feed forward path. Description of elements common to both FIG. 1 and FIG. 2 is omitted here for brevity, and a person having ordinary skill in the art will readily understand the applicability of such description to FIG. 2 upon viewing FIG. 2.

A first branch of the feed forward path of the transconductance amplifier stage **202** includes the impedance circuit **116** and inverter(s) **118** electrically connected between the first feed forward path node **154** and the intermediate node **152** like described above with respect to FIG. 1. A second branch of the feed forward path of the transconductance amplifier stage **202** includes an impedance circuit **216** and one or more inverters **218-1** to **218-k** (collectively or individually, inverter(s) **218**). The impedance circuit **216** includes a resistor **220** and a capacitor **222** as a simple example.

The impedance circuit **216** has a first terminal electrically connected to the first feed forward path node **154**. Hence, in the illustrated example, the output node of the inverter **112**,

the output node of the inverter **114**, the first terminal of the resistor **115**, the first terminal of the impedance circuit **116**, and the first terminal of the impedance circuit **216** are electrically connected together at the first feed forward path node **154**. A second terminal of the impedance circuit **116** is electrically connected to a third feed forward path node **232**. In the illustrated example, the resistor **220** has a first terminal that is the first terminal of the impedance circuit **216**, which is electrically connected to the first feed forward path node **154**. A second terminal of the resistor **220** (opposite from the first terminal of the resistor **220**) is electrically connected to a first terminal of the capacitor **222**, which together form the second terminal of the impedance circuit **216** that is electrically connected to the third feed forward path node **232**. A second terminal of the capacitor **222** (opposite from the first terminal of the capacitor **222**) is electrically connected to a ground node. The resistor **220** and capacitor **222** are shown for illustration purposes. Any impedance circuit can be implemented to obtain a desired frequency response. In some examples, the impedance circuit **216** can include a combination of a number of resistors, a number of capacitors, and/or a number of inductors. Any impedance, such as a result of the resistance of the resistor **220** and/or capacitance of the capacitor **222**, can be and/or include an explicitly formed component in the circuit, or can be and/or include a parasitic impedance in the circuit.

The third feed forward path node **232** is further electrically connected to respective input nodes of the one or more inverters **218**. Respective output nodes of the one or more inverters **218** are electrically connected to the intermediate node **152**. Hence, if multiple inverters **218** are implemented, the inverters **218** are electrically connected in parallel.

In some examples, any or each of the inverters **110**, **112**, **114**, **118**, **218** are complementary device inverters, such as CMOS inverters. In some examples, any or each of the inverters **130** are complementary device inverters, such as CMOS inverters.

In some examples, any or each of the components of the CTLE circuit **200** are programmable like described above with respect to FIG. **1**. Programmability of any component(s) can permit the CTLE circuit **200** to be dynamically tunable to achieve a desired frequency response.

In operation, the transconductance amplifier stage **202** converts an input voltage ( $v_i$ ) on the input voltage ( $v_i$ ) node **150** to a current **260** that is output from the transconductance amplifier stage **202** and input into the transimpedance amplifier stage **104**. The transimpedance amplifier stage **104** converts the current **260** to an output voltage ( $v_o$ ) output on the output voltage ( $v_o$ ) node **158**. The primary path of the transconductance amplifier stage **202** converts the input voltage ( $v_i$ ) on the input voltage ( $v_i$ ) node **150** to a primary path current **162**. The first branch of the feed forward path of the transconductance amplifier stage **202** converts the input voltage ( $v_i$ ) on the input voltage ( $v_i$ ) node **150** to a first branch feed forward path current **262**, and the second branch of the feed forward path of the transconductance amplifier stage **202** converts the input voltage ( $v_i$ ) on the input voltage ( $v_i$ ) node **150** to a second branch feed forward path current **264**. The primary path current **162**, the first branch feed forward path current **262**, and the second branch feed forward path current **264** sum to form the current **260**.

The feed forward path is configured such that the respective magnitudes of the first branch feed forward path current **262** and the second branch feed forward path current **264** from the feed forward path are subtracted from the primary path current **162** from the primary path. In the illustrated

example, each of the impedance circuits **116**, **216** is configured as a low-pass filter. The impedance circuits **116**, **216** can be configured to provide different frequency responses that generate the first branch feed forward path current **262** and the second branch feed forward path current **264**. The branches, and the respective currents that are generated, can operate like described above with respect to FIG. **1**. The responses of the first branch and the second branch can depend on the response of the inverters **112**, **114** since both branches are electrically connected to the first feed forward path node **154**.

Like previously described, the frequency responses of the inverters **110**, **112**, **114**, **118**, **218** can also affect the current **260**. In various examples, the frequency response of the impedance circuits **116**, **216** can dominate the frequency response of the transconductance amplifier stage **202**, while in other examples, one or more of the inverters **110**, **112**, **114**, **118**, **218** can dominate the frequency response of the transconductance amplifier stage **202**. The programmability of any of the inverters **110**, **112**, **114**, **118**, **218** can be used to implement different frequency responses of the respective inverter(s). Additionally, any other circuit configuration can be implemented for the impedance circuits **116**, **216** to achieve a desired frequency response. In some examples, each of the impedance circuits **116**, **216** can be configured as or including a low-pass filter, a high-pass filter, a notch filter, a band-pass filter, or the like. Any filter can have any combination of poles and/or zeros in its transfer function.

FIG. **3** is a circuit schematic of another CTLE circuit **300** according to some examples. The CTLE circuit **300** includes a transconductance amplifier stage **302** and the transimpedance amplifier stage **104**. The transconductance amplifier stage **302** of FIG. **3** is similar to the transconductance amplifier stage **102** of FIG. **1** but with multiple feed forward paths. Two feed forward paths are illustrated in FIG. **2** and described below. In other examples, any number of feed forward paths can be implemented. Additionally, any combination or number of branches in any feed forward path can be implemented. Description of elements common to both FIG. **1** and FIG. **3** is omitted here for brevity, and a person having ordinary skill in the art will readily understand the applicability of such description to FIG. **3** upon viewing FIG. **3**.

The transconductance amplifier stage **302** further includes a second feed forward path. The transconductance amplifier stage **302** includes an inverter **312**, an inverter **314**, a resistor **315**, an impedance circuit **316**, and one or more inverters **318-1** to **318-l** (collectively or individually, inverter(s) **318**) in the second feed forward path. The impedance circuit **316** includes a resistor **320** and a capacitor **322** as a simple example.

The inverter **312** has an input node electrically connected to the input voltage ( $v_i$ ) node **150** and has an output node electrically connected to a third feed forward path node **332**. In the illustrated example, the inverter **314** has an output node electrically connected to the third feed forward path node **332**, and a first terminal of the resistor **315** is electrically connected to the third feed forward path node **332**. A second terminal of the resistor **315** (opposite from the first terminal) is electrically connected to an input node **333** of the inverter **314**. In some examples, the resistor **315** can be omitted, and the input node and output node of the inverter **314** can each be electrically connected to the third feed forward path node **332**. The impedance circuit **316** has a first terminal electrically connected to the third feed forward path node **332**. Hence, in the illustrated example, the output node of the inverter **312**, the output node of the inverter **314**, the first terminal of the resistor **315**, and the first terminal of the

impedance circuit **316** are electrically connected together at the third feed forward path node **332**.

A second terminal of the impedance circuit **316** is electrically connected to a fourth feed forward path node **334**. In the illustrated example, the resistor **320** has a first terminal that is the first terminal of the impedance circuit **316**, which is electrically connected to the third feed forward path node **332**. A second terminal of the resistor **320** (opposite from the first terminal of the resistor **320**) is electrically connected to a first terminal of the capacitor **322**, which together form the second terminal of the impedance circuit **316** that is electrically connected to the fourth feed forward path node **334**. A second terminal of the capacitor **322** (opposite from the first terminal of the capacitor **322**) is electrically connected to a ground node. The resistor **320** and capacitor **322** are shown for illustration purposes. Any impedance circuit can be implemented to obtain a desired frequency response. In some examples, the impedance circuit **316** can include a combination of a number of resistors, a number of capacitors, and/or a number of inductors. Any impedance, such as a result of the resistance of the resistor **320** and/or capacitance of the capacitor **322**, can be and/or include an explicitly formed component in the circuit, or can be and/or include a parasitic impedance in the circuit.

The fourth feed forward path node **334** is further electrically connected to respective input nodes of the one or more inverters **318**. Respective output nodes of the one or more inverters **318** are electrically connected to the intermediate node **152**. Hence, if multiple inverters **318** are implemented, the inverters **318** are electrically connected in parallel.

In some examples, any or each of the inverters **110**, **112**, **114**, **118**, **312**, **314**, **318** are complementary device inverters, such as CMOS inverters. In some examples, any or each of the inverters **130** are complementary device inverters, such as CMOS inverters.

In some examples, any or each of the components of the CTLE circuit **300** are programmable like described above with respect to FIG. 1. Programmability of any component(s) can permit the CTLE circuit **300** to be dynamically tunable to achieve a desired frequency response.

In operation, the transconductance amplifier stage **302** converts an input voltage ( $v_i$ ) on the input voltage ( $v_i$ ) node **150** to a current **360** that is output from the transconductance amplifier stage **302** and input into the transimpedance amplifier stage **104**. The transimpedance amplifier stage **104** converts the current **360** to an output voltage ( $v_o$ ) output on the output voltage ( $v_o$ ) node **158**. The primary path of the transconductance amplifier stage **302** converts the input voltage ( $v_i$ ) on the input voltage ( $v_i$ ) node **150** to a primary path current **162**. The first feed forward path of the transconductance amplifier stage **302** converts the input voltage ( $v_i$ ) on the input voltage ( $v_i$ ) node **150** to a first feed forward path current **362**, and the second feed forward path of the transconductance amplifier stage **302** converts the input voltage ( $v_i$ ) on the input voltage ( $v_i$ ) node **150** to a second feed forward path current **364**. The primary path current **162**, the first feed forward path current **362**, and the second feed forward path current **364** sum to form the current **260**.

The first and second feed forward paths are configured such that the respective magnitudes of the first feed forward path current **362** from the first feed forward path (e.g., including the inverters **112**, **114**, **118** and impedance circuit **116**) and the second feed forward path current **364** from the second feed forward path are subtracted from the primary path current **162** from the primary path. In the illustrated example, each of the impedance circuits **116**, **316** is config-

ured as a low-pass filter. The impedance circuits **116**, **316** can be configured to provide different frequency responses that generate the first feed forward path current **362** and the second feed forward path current **364**. The first and second feed forward paths, and the respective currents that are generated, can operate like described above with respect to FIG. 1.

Like previously described, the frequency responses of the inverters **110**, **112**, **114**, **118**, **312**, **314**, **318** can also affect the current **360**. More specifically, the frequency responses of the inverters **112**, **114**, **118** can affect the first feed forward path current **362**, and the frequency responses of the inverters **312**, **314**, **318** can affect the second feed forward path current **364**. The first feed forward path can have a response that is independent from the inverters **312**, **314**, and the second feed forward path can have a response that is independent from the inverters **112**, **114**. In various examples, the frequency response of the impedance circuits **116**, **316** can dominate the frequency response of the transconductance amplifier stage **302**, while in other examples, one or more of the inverters **110**, **112**, **114**, **118**, **312**, **314**, **318** can dominate the frequency response of the transconductance amplifier stage **302**. The programmability of any of the inverters **110**, **112**, **114**, **118**, **312**, **314**, **318** can be used to implement different frequency responses of the respective inverter(s). Additionally, any other circuit configuration can be implemented for the impedance circuits **116**, **316** to achieve a desired frequency response. In some examples, each of the impedance circuits **116**, **316** can be configured as or including a low-pass filter, a high-pass filter, a notch filter, a band-pass filter, or the like. Any filter can have any combination of poles and/or zeros in its transfer function.

FIG. 4 is a circuit schematic of a CTLE circuit **400** according to some examples. The CTLE circuit **400** includes a transconductance amplifier stage **402** and a transimpedance amplifier stage **104**. The transimpedance amplifier stage **104** is like described above with respect to FIG. 1, and hence, description here of the transimpedance amplifier stage **104** is omitted.

The transconductance amplifier stage **402** includes a primary path and a feed forward path. The transconductance amplifier stage **402** includes one or more inverters **410-1** to **410-h** (collectively or individually, inverter(s) **410**) in the primary path, and includes an inverter **412**, an inverter **414**, a resistor **416**, and an impedance circuit **418** in the feed forward path. The impedance circuit **418** includes a capacitor **422** as a simple example.

Each inverter **410** (whether one is implemented or multiple are implemented) has an input node electrically connected to an input voltage ( $v_i$ ) node **450** and has an output node electrically connected to an intermediate node **452**. The input voltage ( $v_i$ ) node **450** can function as an input node of the transconductance amplifier stage **402**. If multiple inverters **410** are implemented, the inverters **410** are electrically connected in parallel. The intermediate node **452** can be an output node of the transconductance amplifier stage **402** and an input node of the transimpedance amplifier stage **104**.

The inverter **412** has an input node electrically connected to the input voltage ( $v_i$ ) node **450** and has an output node electrically connected to a first feed forward path node **454**. The inverter **414** has an input node electrically connected to a second feed forward path node **456** and an output node electrically connected to the first feed forward path node **454**. The resistor **416** has a first terminal electrically connected to the first feed forward path node **454** and has a second terminal electrically connected to the second feed forward path node **456**. Hence, the resistor **416** is electrically

connected between the input node and the output node of the inverter **414**. The impedance circuit **418** has a first terminal electrically connected to the first feed forward path node **454**. Hence, the output node of the inverter **412**, the output node of the inverter **414**, the first terminal of the resistor **416**, and the first terminal of the impedance circuit **418** are electrically connected together at the first feed forward path node **454**.

A second terminal of the impedance circuit **418** is electrically connected to the intermediate node **452**. In the illustrated example, the capacitor **420** has a first terminal that is the first terminal of the impedance circuit **418**, which is electrically connected to the first feed forward path node **454**. A second terminal of the capacitor **420** (opposite from the first terminal of the capacitor **420**) is the second terminal of the impedance circuit **418** that is electrically connected to the intermediate node **452**. The capacitor **420** is shown for illustration purposes. The capacitor **420** can implement a high-pass filter. Any impedance circuit can be implemented to obtain a desired frequency response. In some examples, the impedance circuit **418** can include a combination of a number of resistors, a number of capacitors, and/or a number of inductors. Any impedance, such as a result of the capacitance of the capacitor **420**, can be and/or include an explicitly formed component in the circuit, or can be and/or include a parasitic impedance in the circuit.

In some examples, any or each of the inverters **410**, **412**, **414** are complementary device inverters, such as CMOS inverters. In some examples, any or each of the inverters **130** are complementary device inverters, such as CMOS inverters.

In some examples, any or each of the components of the CTLE circuit **400** are programmable. Programmability of any component can be implemented by a device, like a switch such as a transistor, that selectively electrically connects the respective component in the CTLE circuit **400** and can be implemented by tuning or biasing the respective component to implement a desired frequency response and/or have a desired electrical characteristic (e.g., response, impedance, conductance, etc.). Various examples of programmable components are described below. Programmability of any component(s) can permit the CTLE circuit **400** to be dynamically tunable to achieve a desired frequency response.

In operation, the transconductance amplifier stage **402** converts an input voltage ( $v_i$ ) on the input voltage ( $v_i$ ) node **450** to a current **460** that is output from the transconductance amplifier stage **402** and input into the transimpedance amplifier stage **104**. The transimpedance amplifier stage **104** converts the current **460** to an output voltage ( $v_o$ ) output on the output voltage ( $v_o$ ) node **158**. The primary path of the transconductance amplifier stage **402** converts the input voltage ( $v_i$ ) on the input voltage ( $v_i$ ) node **450** to a primary path current **462**, and the feed forward path of the transconductance amplifier stage **402** converts the input voltage ( $v_i$ ) on the input voltage ( $v_i$ ) node **450** to a feed forward path current **464**. The primary path current **462** and the feed forward path current **464** sum to form the current **460**.

The feed forward path is configured such that the magnitude of the feed forward path current **464** from the feed forward path is added to the primary path current **462** from the primary path. Hence, the transconductance amplifier stage **402** may be referred to as having additive feed forward. In the illustrated example, the impedance circuit **418** is configured as a high-pass filter. Hence, in the illustrated example and assuming a same magnitude of an input voltage ( $v_i$ ) across relevant frequencies, the magnitude of the

feed forward path current **464** can generally be greater at higher frequencies (e.g., greater than the 3 dB roll off frequency) and can generally be lower at lower frequencies (e.g., from DC (e.g., 0 Hz) to the 3 dB roll off frequency). Accordingly, in such example, the feed forward path can cause a greater magnitude of current to be added to the primary path current **462** at higher frequencies to generate the current **460**, while causing a lower magnitude of current to be added to the primary path current **462** at lower frequencies. In such examples, the current **460** can be lower at low frequencies and higher at high frequencies, which can cause peaking of the current **460** at higher frequencies. Generally, the gain of the frequency response of the transconductance amplifier stage **402** in this example can be greater at higher frequencies (e.g., peak at those higher frequencies) and can be lower at lower frequencies.

The frequency responses of the inverters **410**, **412**, **414** can also affect the current **460**. In various examples, the frequency response of the impedance circuit **418** can dominate the frequency response of the transconductance amplifier stage **402**, while in other examples, one or more of the inverters **410**, **412**, **414** can dominate the frequency response of the transconductance amplifier stage **402**. The programmability of any of the inverters **410**, **412**, **414** can be used to implement different frequency responses of the respective inverter(s). Additionally, any other circuit configuration can be implemented for the impedance circuit **418** to achieve a desired frequency response. In some examples, the impedance circuit **418** can be configured as or including a low-pass filter, a high-pass filter, a notch filter, a band-pass filter, or the like. Any filter can have any combination of poles and/or zeros in its transfer function.

FIG. **5** is a circuit schematic of another CTLE circuit **500** according to some examples. The CTLE circuit **500** includes a transconductance amplifier stage **502** and the transimpedance amplifier stage **104**. The transconductance amplifier stage **502** of FIG. **5** is similar to the transconductance amplifier stage **402** of FIG. **4** but with multiple feed forward paths. Two feed forward paths are illustrated in FIG. **5** and described below. In other examples, any number of feed forward paths can be implemented. Description of elements common to both FIG. **4** and FIG. **5** is omitted here for brevity, and a person having ordinary skill in the art will readily understand the applicability of such description to FIG. **5** upon viewing FIG. **5**.

The transconductance amplifier stage **502** further includes a second feed forward path. The transconductance amplifier stage **502** includes an inverter **512**, an inverter **514**, a resistor **516**, and an impedance circuit **518** in the second feed forward path. The impedance circuit **518** includes a capacitor **520** as a simple example.

The inverter **512** has an input node electrically connected to the input voltage ( $v_i$ ) node **450** and has an output node electrically connected to a third feed forward path node **532**. The inverter **514** has an input node electrically connected to a fourth feed forward path node **534** and an output node electrically connected to the third feed forward path node **532**. The resistor **516** has a first terminal electrically connected to the third feed forward path node **532** and has a second terminal electrically connected to the fourth feed forward path node **534**. Hence, the resistor **516** is electrically connected between the input node and the output node of the inverter **514**. The impedance circuit **518** has a first terminal electrically connected to the third feed forward path node **532**. Hence, the output node of the inverter **512**, the output node of the inverter **514**, the first terminal of the resistor **516**,

and the first terminal of the impedance circuit **518** are electrically connected together at the third feed forward path node **532**.

A second terminal of the impedance circuit **518** is electrically connected to the intermediate node **452**. In the illustrated example, the capacitor **520** has a first terminal that is the first terminal of the impedance circuit **518**, which is electrically connected to the third feed forward path node **532**. A second terminal of the capacitor **520** (opposite from the first terminal of the capacitor **520**) is the second terminal of the impedance circuit **518** that is electrically connected to the intermediate node **452**. The capacitor **520** is shown for illustration purposes. Any impedance circuit can be implemented to obtain a desired frequency response. In some examples, the impedance circuit **518** can include a combination of a number of resistors, a number of capacitors, and/or a number of inductors. Any impedance, such as a result of the capacitance of the capacitor **520**, can be and/or include an explicitly formed component in the circuit, or can be and/or include a parasitic impedance in the circuit.

In some examples, any or each of the inverters **410**, **412**, **414**, **512**, **514** are complementary device inverters, such as CMOS inverters. In some examples, any or each of the inverters **130** are complementary device inverters, such as CMOS inverters.

In some examples, any or each of the components of the CTLE circuit **500** are programmable like described above with respect to FIG. 4. Programmability of any component(s) can permit the CTLE circuit **500** to be dynamically tunable to achieve a desired frequency response.

In operation, the transconductance amplifier stage **502** converts an input voltage ( $v_i$ ) on the input voltage ( $v_i$ ) node **450** to a current **560** that is output from the transconductance amplifier stage **502** and input into the transimpedance amplifier stage **104**. The transimpedance amplifier stage **104** converts the current **560** to an output voltage ( $v_o$ ) output on the output voltage ( $v_o$ ) node **158**. The primary path of the transconductance amplifier stage **502** converts the input voltage ( $v_i$ ) on the input voltage ( $v_i$ ) node **450** to a primary path current **162**. The first feed forward path of the transconductance amplifier stage **502** converts the input voltage ( $v_i$ ) on the input voltage ( $v_i$ ) node **450** to a first feed forward path current **562**, and the second feed forward path of the transconductance amplifier stage **502** converts the input voltage ( $v_i$ ) on the input voltage ( $v_i$ ) node **450** to a second feed forward path current **564**. The primary path current **462**, the first feed forward path current **562**, and the second feed forward path current **564** sum to form the current **560**.

The first and second feed forward paths are configured such that the respective magnitudes of the first feed forward path current **562** from the first feed forward path (e.g., including the inverters **412**, **414** and impedance circuit **418**) and the second feed forward path current **564** from the second feed forward path are added to the primary path current **462** from the primary path. In the illustrated example, each of the impedance circuits **418**, **518** is configured as a high-pass filter. The impedance circuits **418**, **518** can be configured to provide different frequency responses that generate the first feed forward path current **562** and the second feed forward path current **564**. The first and second feed forward paths, and the respective currents that are generated, can operate like described above with respect to FIG. 4.

Like previously described, the frequency responses of the inverters **410**, **412**, **414**, **512**, **514** can also affect the current **560**. More specifically, the frequency responses of the

inverters **412**, **414** can affect the first feed forward path current **562**, and the frequency responses of the inverters **512**, **514** can affect the second feed forward path current **564**. The first feed forward path can have a response that is independent from the inverters **512**, **514**, and the second feed forward path can have a response that is independent from the inverters **412**, **414**. In various examples, the frequency response of the impedance circuits **418**, **518** can dominate the frequency response of the transconductance amplifier stage **502**, while in other examples, one or more of the inverters **410**, **412**, **414**, **512**, **514** can dominate the frequency response of the transconductance amplifier stage **502**. The programmability of any of the inverters **410**, **412**, **414**, **512**, **514** can be used to implement different frequency responses of the respective inverter(s). Additionally, any other circuit configuration can be implemented for the impedance circuits **418**, **518** to achieve a desired frequency response. In some examples, each of the impedance circuits **418**, **518** can be configured as or including a low-pass filter, a high-pass filter, a notch filter, a band-pass filter, or the like. Any filter can have any combination of poles and/or zeros in its transfer function.

FIG. 6 illustrates n number of parallel-connected complementary device (e.g., CMOS) inverters **602-1**, **602-2**, through **602-n** (collectively or individually, inverter(s) **602**) according to some examples. An inverter **602** illustrated in FIG. 6 can be implemented for any inverter of the CTLE circuits of FIGS. 1-5. As noted above, a single inverter **602** can be implemented in various instances without being electrically connected in parallel. The n number of inverters **602** are shown for the purpose of illustrating possible parallel connections. Each inverter **602** in FIG. 6 is not programmable.

An inverter **602** includes m number of p-type transistors **604-1** to **604-m** (e.g., p-type fin field effect transistors (FinFETs)) and an n-type transistor **606** (e.g., an n-type FinFET). As illustrated, a ratio of p-type transistors **604** to n-type transistors **606** is m:1. Other examples contemplate any ratio. For example, an example contemplates an inverter **602** having one p-type transistor **604** and one n-type transistor **606** such that the ratio is 1:1. The ratio can be selected for an inverter **602**, and a corresponding number of p-type and n-type transistors implemented in the inverter **602**, to balance drivability between the p-type transistor(s) and the n-type transistor(s).

A respective gate node of the p-type transistor **604** is electrically connected to an input voltage ( $v_i$ ) node. A respective source node of the p-type transistor **604** is electrically connected to a power supply voltage ( $V_{DD}$ ) node, and a respective drain node of the p-type transistor **604** is electrically connected to an output voltage ( $v_o$ ) node. Hence, the m number of p-type transistors **604** are electrically connected in parallel in an inverter **602**. A gate node of the n-type transistor **606** is electrically connected to the input voltage ( $v_i$ ) node. A drain node of the n-type transistor **606** is electrically connected to the output voltage ( $v_o$ ) node, and a source node of the n-type transistor **606** is electrically connected to a ground node. A person of ordinary skill in the art will readily understand how additional n-type transistors **606** can be connected in parallel to achieve other ratios described above.

FIG. 7 illustrates n number of parallel-connected complementary device (e.g., CMOS) inverters **702-1**, **702-2**, through **702-n** (collectively or individually, inverter(s) **702**) according to some examples. An inverter **702** illustrated in FIG. 7 can be implemented for any inverter of the CTLE circuits of FIGS. 1-5. The n number of inverters **702** are shown for the purpose of illustrating possible parallel con-

nections. Each inverter **702** in FIG. 7 is programmable. Each inverter **702** is programmable to selectively electrically connect or disconnect the p-type transistors **604** and n-type transistor **606** in the inverter **702** between the power supply voltage ( $V_{DD}$ ) node and the ground node.

An inverter **702** includes the  $m$  number of p-type transistors **604** and the n-type transistor **606** generally as described above with respect to FIG. 6. The inverter **702** further includes  $m$  number of p-type transistors **704-1** to **704- $m$**  (e.g., p-type FinFETs) and an n-type transistor **706** (e.g., an n-type FinFET).

A respective source node of the p-type transistor **704** is electrically connected to the power supply voltage ( $V_{DD}$ ) node, and a respective drain node of the p-type transistor **704** is electrically connected to a respective source node of a corresponding p-type transistor **604**. Hence, each p-type transistor **604** in the inverter **702** has a corresponding p-type transistor **704** where the channels of the p-type transistors **604**, **704** are electrically connected in series. A respective gate node of the p-type transistor **704** is electrically connected to a complementary enable signal ( $ENB_x$ ) node of the inverter **702- $x$** , where  $x$  identifies the corresponding inverter **702** in which the particular component is disposed or to which the particular signal is coupled (e.g.,  $x$  is 1 for inverter **702-1**) in this instance.

The source node of the n-type transistor **606** is electrically connected to a drain node of the n-type transistor **706**, and a source node of the n-type transistor **706** is electrically connected to the ground node. Hence, the n-type transistor **606** in the inverter **702** has a corresponding n-type transistor **706** where the channels of the n-type transistors **606**, **706** are electrically connected in series. A respective gate node of the n-type transistor **706** is electrically connected to an enable signal ( $EN_x$ ) node of the inverter **702- $x$** . The enable signal ( $EN_x$ ) and the complementary enable signal ( $ENB_x$ ) on the respective nodes of the inverter **702- $x$**  are logical complements of each other.

In operation, the enable signal ( $EN_x$ ) can be a logical “1” or a logical “0”, and the complementary enable signal ( $ENB_x$ ) can be a complementary value. When the enable signal ( $EN_x$ ) is a logical “1” and the complementary enable signal ( $ENB_x$ ) is a logical “0”, the p-type transistors **704** and n-type transistor **706** act as closed switches to electrically couple the p-type transistors **604** and n-type transistor **606** between the power supply voltage ( $V_{DD}$ ) node and the ground node. In this state, the p-type transistors **604** and n-type transistor **606** are operational to provide or contribute to a response on the output voltage ( $v_o$ ) node. When the enable signal ( $EN_x$ ) is a logical “0” and the complementary enable signal ( $ENB_x$ ) is a logical “1”, the p-type transistors **704** and n-type transistor **706** act as open switches to electrically de-couple the p-type transistors **604** and n-type transistor **606** between the power supply voltage ( $V_{DD}$ ) node and the ground node. In this state, the p-type transistors **604** and n-type transistor **606** do not provide or contribute to a response on the output voltage ( $v_o$ ) node.

Hence, by selectively setting the enable signal ( $EN_x$ ) for a given inverter **702- $x$** , that inverter **702- $x$**  can contribute or provide a current weighting or impedance or frequency response based on an input signal input on the input voltage ( $v_i$ ) node by outputting an output signal on the output voltage ( $v_o$ ) node. Any combination or number of inverters **702** can have a respective enable signal set to provide any desired current weighting or impedance or frequency response.

In some examples, the state or value of an enable signal can be stored in a storage element, such as memory, a

register, or the like. An output node of the storage element can be electrically coupled directly or through intermediate buffers and/or logic and/or voltage level-shifters to a respective gate node to provide the enable signal to the gate node.

The output node of the storage element can also be electrically coupled to an input node of an inverter (e.g., like an inverter **602** in FIG. 6) that has an output node electrically coupled to a respective gate node to provide the complementary enable signal to the gate node.

FIG. 8 illustrates  $n$  number of parallel-connected complementary device (e.g., CMOS) inverters **802-1**, **802-2**, through **802- $n$**  (collectively or individually, inverter(s) **802**) according to some examples. An inverter **802** illustrated in FIG. 8 can be implemented for any inverter of the CTLE circuits of FIGS. 1-5. The  $n$  number of inverters **802** are shown for the purpose of illustrating possible parallel connections. Each inverter **802** in FIG. 8 is programmable. Each inverter **802** is programmable to bias the p-type transistors **704** and n-type transistor **706** in the inverter **802**.

An inverter **802** includes the  $m$  number of p-type transistors **604**, **704** and the n-type transistor **606**, **706** generally as described above with respect to FIGS. 6 and 7. A respective gate node of the p-type transistor **704** is electrically connected to a respective p-type device bias voltage ( $v_{bpx}$ ) node of the inverter **802- $x$** , where  $x$  identifies the corresponding inverter **802** in which the particular component is disposed or to which the particular signal is coupled (e.g.,  $x$  is 1 for inverter **802-1**) in this instance. A respective gate node of the n-type transistor **706** is electrically connected to a respective n-type device bias voltage ( $v_{bnx}$ ) node of the inverter **802- $x$** .

The bias voltages on the p-type device bias voltage ( $v_{bpx}$ ) nodes and the n-type device bias voltage ( $v_{bnx}$ ) node bias the inverter **802- $x$**  to have a desired current or impedance or response (e.g., a response output on the output voltage ( $v_o$ ) node based on the input voltage input on the input voltage ( $v_i$ ) node). Hence, by biasing a given inverter **802- $x$** , that inverter **802- $x$**  can contribute or provide a desired current or impedance or frequency response based on an input signal input on the input voltage ( $v_i$ ) node by outputting an output signal on the output voltage ( $v_o$ ) node. Any combination or number of inverters **802** can be biased to provide any desired current or impedance or frequency response.

Additionally, when respective bias voltages are at a respective power rail (e.g.,  $V_{DD}$  or ground) to be a logical “1” or “0”, the inverters **802** can be selectively electrically coupled or de-coupled between the power supply voltage ( $V_{DD}$ ) node and the ground node, like described above with respect to FIG. 7.

In some examples, a digital value corresponding to a bias voltage can be stored in a storage element, such as memory, a register, or the like. An output node(s) of the storage element can be electrically coupled directly or through intermediate buffers and/or logic and/or voltage level-shifters to a digital-to-analog converter (DAC) that is configured to generate an analog bias voltage in response to the digital value stored in the storage element. An output node of the DAC can be electrically coupled to a respective gate node to provide the bias voltage to the gate node. Each bias voltage can likewise have a digital value stored in a storage element that causes a DAC to generate the respective bias voltage.

FIGS. 9 through 14 are circuit schematics of example resistive elements **900**, **1000**, **1100**, **1200**, **1300**, **1400**, respectively, according to some examples. For clarity, any bias node and bias voltage in FIGS. 9 through 14 can be independent and separate from any other bias node and bias voltage, e.g., implemented in an inverter, another program-

mable resistor, or other programmable element. The resistive element **900** of FIG. **9** includes a resistor **902** electrically connected between a first terminal **904** and a second terminal **906**. The resistive element **900** is not programmable. The resistive element **1000** of FIG. **10** includes an n-type transistor **1002** having a source/drain node electrically connected to a first terminal **1004** and having another source/drain node electrically connected to a second terminal **1006**. A gate node of the n-type transistor **1002** is electrically connected to a bias voltage ( $v_{bn}$ ) node. The resistive element **1100** of FIG. **11** includes a p-type transistor **1102** having a source/drain node electrically connected to a first terminal **1104** and having another source/drain node electrically connected to a second terminal **1106**. A gate node of the p-type transistor **1102** is electrically connected to a bias voltage ( $v_{bp}$ ) node.

The resistive element **1200** of FIG. **12** includes a p-type transistor **1202** and an n-type transistor **1204**. The p-type transistor **1202** has a source/drain node electrically connected to a first terminal **1206** and has another source/drain node electrically connected to a second terminal **1208**. The n-type transistor **1204** has a source/drain node electrically connected to the first terminal **1206** and has another source/drain node electrically connected to the second terminal **1208**. A gate node of the p-type transistor **1202** is electrically connected to a bias voltage ( $v_{bp}$ ) node, and a gate node of the n-type transistor **1204** is electrically connected to a bias voltage ( $v_{bn}$ ) node.

The resistive element **1300** of FIG. **13** includes a resistor **1302**, a p-type transistor **1304**, and an n-type transistor **1306**. The resistor **1302** is electrically connected between a first terminal **1308** and a second terminal **1310**. The p-type transistor **1304** has a source/drain node electrically connected to the first terminal **1308** and has another source/drain node electrically connected to the second terminal **1310**. The n-type transistor **1306** has a source/drain node electrically connected to the first terminal **1308** and has another source/drain node electrically connected to the second terminal **1310**. A gate node of the p-type transistor **1304** is electrically connected to a bias voltage ( $v_{bp}$ ) node, and a gate node of the n-type transistor **1306** is electrically connected to a bias voltage ( $v_{bn}$ ) node.

The resistive element **1400** of FIG. **14** includes a resistor **1402**, a p-type transistor **1404**, and an n-type transistor **1406**. A first terminal of the resistor **1402** is electrically connected to a first terminal **1408** of the resistive element **1400**. The p-type transistor **1404** has a source/drain node electrically connected to a second terminal of the resistor **1402** (opposite from the first terminal of the resistor **1402**) and has another source/drain node electrically connected to a second terminal **1410** of the resistive element **1400**. The n-type transistor **1406** has a source/drain node electrically connected to the second terminal of the resistor **1402** and has another source/drain node electrically connected to the second terminal **1410** of the resistive element **1400**. A gate node of the p-type transistor **1404** is electrically connected to a bias voltage ( $v_{bp}$ ) node, and a gate node of the n-type transistor **1406** is electrically connected to a bias voltage ( $v_{bn}$ ) node.

The resistive elements **1000**, **1100**, **1200**, **1300**, **1400** can be programmable. For each of the bias voltage ( $v_{bp}$ ,  $v_{bn}$ ) nodes of the resistive elements **1000**, **1100**, **1200**, **1300**, **1400**, a digital value corresponding to a bias voltage can be stored in a storage element, such as memory, a register, or the like. An output node(s) of the storage element can be electrically coupled to a DAC that is configured to generate an analog bias voltage in response to the digital value stored in the storage element. An output node of the DAC can be

electrically coupled to the respective bias voltage node to provide the bias voltage. Hence, by writing a desired digital value to an appropriate storage element, the bias voltage can be programmable. The bias voltage on a bias voltage node can result in a corresponding resistance through the channel of the p-type or n-type transistor to which the bias voltage is applied. Accordingly, by writing a desired value to an appropriate storage element, the resistance of a resistive element can be programmatically set.

FIG. **15** is a circuit schematic of an impedance array **1500** according to some examples. The impedance array **1500** includes q number of impedance elements **1502-1**, **1502-2** to **1502-q** (individually or collectively, impedance element(s) **1502**) and q number of switches **1504-1**, **1504-2** to **1504-q** (individually or collectively, switch(es) **1504**). An impedance element **1502** is electrically connected in series with a corresponding switch **1504**. The serially connected pairs of the impedance element **1502** and switch **1504** are electrically connected in parallel between a first terminal **1506** of the impedance array **1500** and a second terminal **1508** of the impedance array **1500**.

Each switch **1504** further has a control ( $C_x$ ) node. Each switch **1504** is configured to be selectively opened or closed based on a signal received at the control ( $C_x$ ) node. Each switch **1504** can be a transistor (e.g., a p-type or n-type transistor), a transmission gate, or other switch. Each impedance element **1502** can be or include a resistive element (e.g., as shown in FIGS. **9-14**), a capacitor, an inductor, or any combination or permutation thereof.

The impedance array **1500** is configured to selectively electrically connect or disconnect impedance elements in parallel based on the state (e.g., open or closed) of the switches **1504**. The impedance array **1500** is programmable. In some examples, a control signal ( $C_x$ ) can be stored in a storage element, such as memory, a register, or the like. An output node of the storage element can be electrically coupled to a respective control ( $C_x$ ) node to provide the control signal ( $C_x$ ) to the control ( $C_x$ ) node to control the state of the corresponding switch **1504**.

FIG. **16** is a circuit schematic of an impedance array **1600** according to some examples. The impedance array **1600** includes r number of impedance elements **1602-1**, **1602-2** to **1602-r** (individually or collectively, impedance element(s) **1602**) and r number of switches **1604-1**, **1604-2** to **1604-r** (individually or collectively, switch(es) **1604**). An impedance element **1602** is electrically connected in parallel with a corresponding switch **1604**. The parallel-connected pairs of the impedance element **1602** and switch **1604** are electrically connected in series between a first terminal **1606** of the impedance array **1600** and a second terminal **1608** of the impedance array **1600**.

Each switch **1504** further has a control ( $C_x$ ) node. Each switch **1504** is configured to be selectively opened or closed based on a signal received at the control ( $C_x$ ) node. Each switch **1504** can be a transistor (e.g., a p-type or n-type transistor), a transmission gate, or other switch. Each impedance element **1502** can be or include a resistive element (e.g., as shown in FIGS. **9-14**), a capacitor, an inductor, or any combination or permutation thereof.

The impedance array **1600** is configured to selectively electrically connect or disconnect impedance elements in series based on the state (e.g., open or closed) of the switches **1604**. When a switch **1604** is open, the corresponding impedance element **1602** of the parallel-connected pair is electrically coupled in series with any other impedance element in the impedance array **1600**. When a switch **1604** is closed, the corresponding impedance element **1602** of the

parallel-connected pair is electrically shorted and bypassed by the closed switch **1604**, and hence, that impedance element **1602** is not coupled in series with any other impedance element in the impedance array **1600**. The impedance array **1600** is programmable. In some examples, a control signal ( $C_x$ ) can be stored in a storage element, such as memory, a register, or the like. An output node of the storage element can be electrically coupled to a respective control ( $C_x$ ) node to provide the control signal ( $C_x$ ) to the control ( $C_x$ ) node to control the state of the corresponding switch **1604**.

Any impedance circuit in a CTLE circuit, such as in FIGS. **1-5**, can implement any resistive element and/or impedance array illustrated in and described with respect to FIGS. **9-16**.

FIG. **17** is a circuit schematic of a transimpedance amplifier stage **1700** according to some examples. The transimpedance amplifier stage **1700** is a modification of the transimpedance amplifier stage **104** of FIGS. **1-5** to illustrate another impedance circuit that can be implemented in a CTLE circuit. The transimpedance amplifier stage **1700** includes inverter(s) **130**, inductors **1702**, **1704**, **1708**, **1712**, **1718**, resistors **1706**, **1714**, and capacitors **1710**, **1716**. Any of the inductors, resistors, and capacitors can be programmable and can be implemented as illustrated in and described above with respect to any of FIGS. **9-16**.

A first terminal of the inductor **1702** is electrically connected to the intermediate node **152/452**, which is the input node of the transimpedance amplifier stage **1700**. A second terminal of the inductor **1702** (opposite from the first terminal) is electrically connected to respective first terminals of the inductor **1704** and the resistor **1706**. A second terminal of the inductor **1704** (opposite from the first terminal) is electrically connected to the input node(s) of the inverter(s) **130**. A second terminal of the resistor **1706** (opposite from the first terminal) is electrically connected to respective first terminals of the inductor **1708** and the capacitor **1710**.

Output node(s) of the inverter(s) **130** are electrically connected to a first terminal of the inductor **1712**. Respective second terminals (opposite from the first terminal) of the capacitor **1710**, inductor **1708**, and inductor **1712** are electrically connected together and to respective first terminals of the resistor **1714** and the inductor **1718**. A second terminal of the resistor **1714** (opposite from the first terminal) is electrically connected to a first terminal of the capacitor **1716**. A second terminal of the capacitor **1716** (opposite from the first terminal) is electrically connected to a ground node. A second terminal of the inductor **1718** (opposite from the first terminal) is electrically connected to the output voltage ( $v_o$ ) node **158**.

Implementing the inductors **1702**, **1704**, **1708**, **1712**, **1718** as shown in FIG. **17** can permit bandwidth extension and/or additional peaking of the frequency response of the CTLE circuit. For example, shunt peaking may be implemented by implementing the inductor **1708** as shown. Any one or more of the inductors **1702**, **1704**, **1712**, **1718** may be implemented, and any one or more of the inductors **1702**, **1704**, **1712**, **1718** may be omitted. Further, magnetic mutual coupling may be implemented with the inductors **1702**, **1704**, **1712**, **1718**. Additionally, implementing the resistor **1714** and capacitor **1716** as shown can implement a notch filter or a low-pass filter at the output voltage ( $v_o$ ) node **158**.

A CTLE circuit can include programmable elements, such as programmable inverters (like in FIGS. **7** and **8**) and programmable impedance circuits. A CTLE circuit can be non-programmable, or can include a combination of programmable and non-programmable elements. Programmability of a CTLE circuit can enable setting different DC or

low frequency gains of the frequency response of the CTLE circuit, setting different poles in the frequency response, and/or setting different zeros in the frequency response.

Programmability of a CTLE circuit can permit the CTLE circuit to be implemented in a broad number of applications. For example, different applications can have communication channels that have different frequency responses, and by programming the CTLE circuit, the CTLE circuit can implement an appropriate frequency response to equalize the signal that is communicated through the communication channel of the application.

In some examples, a CTLE circuit can be programmed by a user manually, and in some examples, the CTLE circuit can be programmed dynamically using an appropriate adaptation algorithm. For example, where a frequency response of a communication channel and of the CTLE circuit can remain substantially static, the CTLE circuit can be programmed once and can continue to operate based on that programming without being reprogrammed. In other examples, operating conditions of the CTLE circuit and/or communication channel can cause a frequency response to change. An adaptation algorithm can detect the changing conditions and can dynamically reprogram the CTLE circuit. For example, a changing temperature and/or operating voltage of the CTLE circuit can affect a frequency response of the CTLE circuit. The changing temperature and/or operating voltage can be detected by a process-voltage-temperature (PVT) monitor, and an adaptation unit (e.g., a processor executing an adaptation algorithm) can responsively reprogram the CTLE circuit based on the changed conditions detected by the PVT monitor.

A CTLE circuit can be single-ended or pseudo differential. Example single-ended CTLE circuits are in FIGS. **1-5**. FIG. **18** is a schematic of a pseudo differential CTLE circuit **1800** according to some examples. The pseudo differential CTLE circuit **1800** includes a first CTLE circuit **1802** (e.g., a single-ended CTLE circuit like in FIGS. **1-5**) and a second CTLE circuit **1804** (e.g., a single-ended CTLE circuit like in FIGS. **1-5**). The first CTLE circuit **1802** and the second CTLE circuit **1804** can be, and can operate, separate and independent from each other. An input voltage ( $v_i$ ) node of the first CTLE circuit **1802** is electrically connected to a positive input voltage ( $v_i^+$ ) node, and an output voltage ( $v_o$ ) node of the first CTLE circuit **1802** is electrically connected to a positive output voltage ( $v_o^+$ ) node. An input voltage ( $v_i$ ) node of the second CTLE circuit **1804** is electrically connected to a negative input voltage ( $v_i^-$ ) node, and an output voltage ( $v_o$ ) node of the second CTLE circuit **1804** is electrically connected to a negative output voltage ( $v_o^-$ ) node. The pseudo differential CTLE circuit **1800** is configured to receive a differential signal on the positive and negative input voltage ( $v_i^+$ ,  $v_i^-$ ) nodes and output a differential signal on the positive and negative output voltage ( $v_o^+$ ,  $v_o^-$ ) nodes. A differential signal output by the pseudo differential CTLE circuit **1800** can have an increased signal-to-noise ratio (SNR).

CTLE circuits can also be cascaded. FIG. **19** is a schematic of cascaded CTLE circuits **1900** according to some examples. The cascaded CTLE circuits **1900** include a first CTLE circuit **1902** and a second CTLE circuit **1904**. Any number of CTLE circuits can be cascaded together. An output voltage ( $v_o$ ) node of the first CTLE circuit **1902** is electrically connected to an input voltage ( $v_i$ ) node of the second CTLE circuit **1904** to cascade the CTLE circuits **1902**, **1904**. Frequency responses of the first CTLE circuit **1902** and the second CTLE circuit **1904** can be the same or



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different. While FIG. 19 illustrates two cascaded CTLE circuits, any number (e.g., three, four, etc.) of CTLE circuits can be cascaded.

Some implementations of a CTLE circuit include wireline serializer-deserializer (SerDes) circuits. The SerDes circuits can be implemented for communication of an electrical signal through a communication channel, or for communication of an optical signal through a communication channel.

A CTLE circuit can be implemented in a receiver circuit or in a transmitter circuit. A CTLE circuit can be implemented before or after a gain stage or other analog circuits in a receiver circuit. A CTLE circuit can be implemented in a transmitter circuit before or after other analog transmission circuits and/or after digital transmission stage stages. In an electrical link interface, a CTLE circuit can serve as either the final driver stage or the pre-driver stages for both fan-out optimization and equalization. Furthermore, a CTLE circuit can be implemented in a transmitter in conjunction with an optical transmitter circuit—placed before an optical transmission circuits or before analog circuits that precede the optical transmission circuits.

FIG. 20 is a flowchart of an operation 2000 of a CTLE circuit according to some examples. The operation 2000 is described in the context of the CTLE circuits 100, 400 of FIGS. 1 and 4, and can also be implemented in any other CTLE circuit described above or another CTLE circuit. Although some aspects of the CTLE circuits 100, 400 are described below, the CTLE circuit implementing the operation 2000 of FIG. 20 can have any feature, component, or aspect that is described above. A person having ordinary skill in the art will readily understand the applicability of the description below to other CTLE circuits.

At block 2002, a transconductance amplifier stage converts an input voltage input to the transconductance amplifier stage to a current with a desired frequency response output from the transconductance amplifier stage. For example, an input voltage ( $v_i$ ) is applied on the input voltage ( $v_i$ ) node 150, 450, and is therefore input to the transconductance amplifier stage 102, 402 of the CTLE circuit 100, 400. The transconductance amplifier stage 102, 402 converts the input voltage ( $v_i$ ) to a current 160, 460 that is output from the transconductance amplifier stage 102.

The transconductance amplifier stage can have a primary path and a feed forward path. For example, the primary path of the transconductance amplifier stage 102, 402 includes one or more inverters 110, 410. The primary path can convert the input voltage to a primary path current. For example, the one or more inverters 110, 410 in the primary path can receive the input voltage ( $v_i$ ) from the input voltage ( $v_i$ ) node 150, 450 and convert the input voltage ( $v_i$ ) to a primary path current 162, 462.

In some examples, the feed forward path can be configured to be subtractive from the primary path. For example, the feed forward path of the transconductance amplifier stage 102 includes an inverter 112, an inverter 114, an impedance circuit 116, and one or more inverters 118. The feed forward path can convert the input voltage ( $v_i$ ) to a feed forward path current. For example, the inverter 112 in the feed forward path can receive the input voltage ( $v_i$ ) from the input voltage ( $v_i$ ) node 150 and, together with the inverter 114, can responsively generate a voltage on the first feed forward path node 154 that is passed through the impedance circuit 116. A passed voltage through the impedance circuit 116 is then converted by the one or more inverters 118 to a feed forward path current 164. The primary path current 162 and the feed forward path current 164 are summed at the

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output node of the transconductance amplifier stage 102 (e.g., the intermediate node 152) to generate the current 160 that is output from the transconductance amplifier stage 102. The primary path and the feed forward path are configured such that the feed forward path current 164 is subtractive from the primary path current 162.

In some examples, the feed forward path can be configured to be additive to the primary path. For example, the feed forward path of the transconductance amplifier stage 402 includes an inverter 412, an inverter 414, and an impedance circuit 418. The feed forward path can convert the input voltage ( $v_i$ ) to a feed forward path current. For example, the inverter 412 in the feed forward path can receive the input voltage ( $v_i$ ) from the input voltage ( $v_i$ ) node 450 and, together with the inverter 414, can responsively generate a current on the first feed forward path node 454 that is passed through the impedance circuit 418. A current from the impedance circuit 418 is a feed forward path current 464. The primary path current 462 and the feed forward path current 464 are summed at the output node of the transconductance amplifier stage 402 (e.g., the intermediate node 452) to generate the current 460 that is output from the transconductance amplifier stage 402. The primary path and the feed forward path are configured such that the feed forward path current 464 is additive to the primary path current 462.

At block 2004, a transimpedance amplifier stage converts the current input to the transimpedance amplifier stage to an output voltage output from the transimpedance amplifier stage. For example, the current 160, 460 is received at an input node of the transimpedance amplifier stage 104 (e.g., the intermediate node 152, 452), and is therefore input to the transimpedance amplifier stage 104 of the CTLE circuit 100, 400. The transimpedance amplifier stage 104 converts the current 160, 460 to an output voltage ( $v_o$ ) that is output from the transimpedance amplifier stage 104 (and hence, from the CTLE circuit 100, 400) on the output voltage ( $v_o$ ) node 158.

FIG. 21 illustrates a field programmable gate array (FPGA) 2100 that may be implemented as a programmable device according to some examples. The FPGA 2100, in the illustrated example, is an integrated circuit that includes a CTLE circuit. The FPGA 2100 includes a large number of different programmable tiles that form a programmable fabric including configurable logic blocks (CLBs) 2102, random access memory blocks (BRAMs) 2104, signal processing blocks (DSPs) 2106, input/output blocks (IOBs) 2108, and configuration and clocking logic (CONFIG/CLOCKS) 2110. The FPGA 2100 also includes a dedicated processor block 2112, digital transceivers 2114, dedicated hardblocks 2116, specialized input/output blocks (IO) 2118 (e.g., configuration ports and clock ports), and other programmable logic 2120 such as digital clock managers, system monitoring logic, and so forth. The hardblocks 2116 can be any circuit, such as a memory controller, a Peripheral Component Interconnect Express (PCIe) hardblock, etc. In some examples, the digital transceivers 2114 include a CTLE circuit as described above.

In the illustrated FPGA 2100, each programmable tile includes a programmable interconnect element (INT) 2130 having connections to input and output terminals of respective programmable interconnect elements 2130 in each adjacent tile and having connections to input and output terminals of a programmable logic element within the same tile. The programmable interconnect elements 2130 taken together implement a programmable interconnect structure for the illustrated FPGA 2100.

As an example, a CLB **2102** includes a configurable logic element (CLE) **2132** that can be programmed to implement user logic plus a single programmable interconnect element **2130**. A BRAM **2104** can include a BRAM logic element (BRL) **2134** in addition to one or more programmable interconnect elements **2130**. Typically, the number of interconnect elements included in a tile depends on the height of the tile. In the illustrated example, a BRAM tile has the same height as five CLBs, but other numbers (e.g., four) can also be used. A signal processing block **2106** can include a DSP logic element (DSPL) **2136** in addition to an appropriate number of programmable interconnect elements **2130**. An input/output block **2108** can include, for example, two instances of an input/output logic element (IOL) **2138** in addition to one instance of the programmable interconnect element **2130**. As will be clear to those of skill in the art, the actual I/O pads connected, for example, to the input/output logic element **2138** typically are not confined to the area of the input/output logic element **2138**.

In the illustrated example, a horizontal area near the center of the die is used for configuration, clock, and other control logic. Vertical columns **2140** extending from this horizontal area or column are used to distribute the clocks and configuration signals across the breadth of the FPGA.

Some FPGAs utilizing the architecture illustrated in FIG. **21** include additional logic blocks that disrupt the regular columnar structure making up a large part of the FPGA. The additional logic blocks can be programmable blocks and/or dedicated logic. For example, processor block **2112** spans several columns of CLBs and BRAMs.

Note that FIG. **21** is intended to illustrate only an exemplary FPGA architecture. For example, the numbers of logic blocks in a row, the relative width of the rows, the number and order of rows, the types of logic blocks included in the rows, the relative sizes of the logic blocks, and the interconnect/logic implementations included at the top of FIG. **21** are purely exemplary. For example, in an actual FPGA, more than one adjacent row of CLBs is typically included wherever the CLBs appear, to facilitate the efficient implementation of user logic, but the number of adjacent CLB rows varies with the overall size of the FPGA.

While the foregoing is directed to specific examples, other and further examples may be devised without departing from the basic scope thereof, and the scope thereof is determined by the claims that follow.

What is claimed is:

**1.** An integrated circuit comprising:

a first transconductance amplifier stage having a first input node and a first output node, the first transconductance amplifier stage including a first path connected between the first input node and the first output node, and a second path electrically connected between the first input node and the first output node, the first path comprising a first plurality of inverters having a first complementary device inverter; and  
a first transimpedance amplifier stage having a second input node and a second output node, the first output node being electrically connected to the second input node, the first transimpedance amplifier stage comprising a second complementary device inverter.

**2.** The integrated circuit of claim **1**, wherein

the first path is configured to output a first current; and the second path is configured to output a second current, the second path being configured such that the second current is subtractive to the first current at the first output node.

**3.** The integrated circuit of claim **1**, wherein the first path is configured to output a first current; and the second path is configured to output a second current, the second path being configured such that the second current is additive to the first current at the first output node.

**4.** The integrated circuit of claim **1**, wherein

the first complementary device inverter comprises an input node electrically connected to the first input node and an output node electrically connected to the first output node; and

the second path comprises a third complementary device inverter, a fourth complementary device inverter, a first impedance circuit, and a fifth complementary device inverter, the third complementary device inverter having an input node electrically connected to the first input node and having an output node electrically connected to an output node of the fourth complementary device inverter and to a first terminal of the first impedance circuit, a second terminal of the first impedance circuit being electrically connected to an input node of the fifth complementary device inverter, an output node of the fifth complementary device inverter being electrically connected to the first output node.

**5.** The integrated circuit of claim **4**, wherein the first transconductance amplifier stage includes:

a third path comprising a sixth complementary device inverter, a seventh complementary device inverter, a second impedance circuit, and an eighth complementary device inverter, the sixth complementary device inverter having an input node electrically connected to the first input node and having an output node electrically connected to an output node of the seventh complementary device inverter and to a first terminal of the second impedance circuit, a second terminal of the second impedance circuit being electrically connected to an input node of the eighth complementary device inverter, an output node of the eighth complementary device inverter being electrically connected to the first output node.

**6.** The integrated circuit of claim **4**, wherein the second path comprises a first branch and a second branch, the first branch comprising the first impedance circuit and the fifth complementary device inverter, the second branch comprising a second impedance circuit and a sixth complementary device inverter, the output node of the third complementary device inverter further being electrically connected to a first terminal of the second impedance circuit, a second terminal of the second impedance circuit being electrically connected to an input node of the sixth complementary device inverter, an output node of the sixth complementary device inverter being electrically connected to the first output node.

**7.** The integrated circuit of claim **4**, wherein at least one of the first complementary device inverter, the second complementary device inverter, the third complementary device inverter, the fourth complementary device inverter, the first impedance circuit, the fifth complementary device inverter, or a combination thereof is programmable.

**8.** The integrated circuit of claim **1**, wherein

the first complementary device inverter comprises an input node electrically connected to the first input node and comprises an output node electrically connected to the first output node; and

the second path comprises a third complementary device inverter, a fourth complementary device inverter, and a first impedance circuit, the third complementary device inverter having an input node electrically connected to

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the first input node and having an output node electrically connected to an output node of the fourth complementary device inverter and to a first terminal of the first impedance circuit, a second terminal of the first impedance circuit being electrically connected to the first output node.

9. The integrated circuit of claim 8, wherein the first transconductance amplifier stage includes:

a third path comprising a fifth complementary device inverter, a sixth complementary device inverter, and a second impedance circuit, the fifth complementary device inverter having an input node electrically connected to the first input node and having an output node electrically connected to an output node of the sixth complementary device inverter and to a first terminal of the second impedance circuit, a second terminal of the second impedance circuit being electrically connected to the first output node.

10. The integrated circuit of claim 8, wherein at least one of the first complementary device inverter, the second complementary device inverter, the third complementary device inverter, the fourth complementary device inverter, the first impedance circuit, or a combination thereof is programmable.

11. The integrated circuit of claim 1, wherein the first transimpedance amplifier stage further comprises an impedance circuit, the second complementary device inverter being electrically connected between the second input node and the second output node, the impedance circuit being electrically connected between the second input node and the second output node.

12. The integrated circuit of claim 1 further comprising: a second transconductance amplifier stage having a third input node and a third output node, the second transconductance amplifier stage comprising a third complementary device inverter; and

a second transimpedance amplifier stage having a fourth input node and a fourth output node, the third output node being electrically connected to the fourth input node, the second transimpedance amplifier stage comprising a fourth complementary device inverter, the first input node and the third input node being configured to receive a differential signal, the second output node and the fourth output node being configured to output a differential signal.

13. The integrated circuit of claim 1 further comprising: a second transconductance amplifier stage having a third input node and a third output node, the second output node being electrically connected to the third input node, the second transconductance amplifier stage comprising a third complementary device inverter; and

a second transimpedance amplifier stage having a fourth input node and a fourth output node, the third output node being electrically connected to the fourth input node, the second transimpedance amplifier stage comprising a fourth complementary device inverter.

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14. An integrated circuit comprising:

a continuous time linear equalizer circuit comprising:

a transconductance amplifier stage having a first input node and a first output node, the transconductance amplifier stage comprising:

a first path comprising a first plurality of inverters electrically connected between the first input node and the first output node, the first plurality of inverters comprises a first complementary device inverter; and

a second path comprising a second complementary device inverter and a first impedance circuit, the second complementary device inverter and the first impedance circuit being electrically connected between the first input node and the first output node; and

a transimpedance amplifier stage having a second input node and a second output node, the first output node being electrically connected to the second input node, the transimpedance amplifier stage comprising a third complementary device inverter electrically connected between the second input node and the second output node.

15. The integrated circuit of claim 14, wherein:

the second path further comprises a fourth complementary device inverter;

an input node of the first complementary device inverter is electrically connected to the first input node;

an output node of the first complementary device inverter is electrically connected to the first output node;

an input node of the second complementary device inverter is electrically connected to the first input node;

an output node of the second complementary device inverter is electrically connected to a first terminal of the first impedance circuit;

a second terminal of the first impedance circuit is electrically connected to an input node of the fourth complementary device inverter; and

an output node of the fourth complementary device inverter is electrically connected to the first output node.

16. The integrated circuit of claim 14, wherein:

an input node of the first complementary device inverter is electrically connected to the first input node;

an output node of the first complementary device inverter is electrically connected to the first output node;

an input node of the second complementary device inverter is electrically connected to the first input node;

an output node of the second complementary device inverter is electrically connected to a first terminal of the first impedance circuit; and

a second terminal of the first impedance circuit is electrically connected to the first output node.

17. The integrated circuit of claim 14, wherein the transimpedance amplifier stage further comprises a second impedance circuit electrically connected between the second input node and the second output node.

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